U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-286 996

Overburden Mineralogy as Related to Ground-Water Chemical Changes in Coal Strip Mining

Colorado School of Mines Research Inst, Golden

Prepared for

Robert S Kerr Environmental Research Lab, Ada, OK

Aug 78

United States
Environmental Protection
Agency

Robert S. Kerr Environmental Research
Laboratory
Ada OK 74820

EPA-600/7-78-156
August 1978

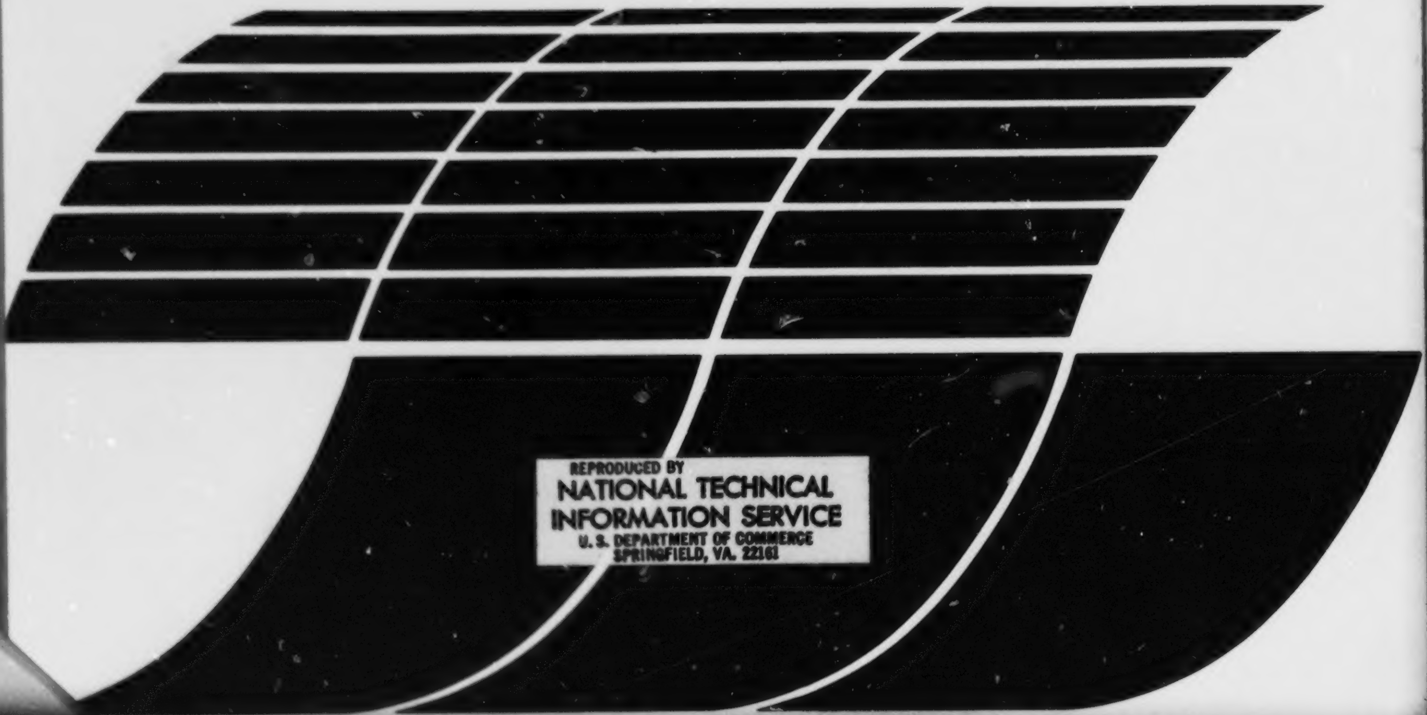
PB 286996

Research and Development

EPA

Overburden Mineralogy as Related to Ground-Water Chemical Changes in Coal Strip Mining

Interagency Energy/Environment R&D Program Report



REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/7-78-156

2.

3. RECIPIENT'S ACCESSION NO.
PB286996

4. TITLE AND SUBTITLE
"OVERBURDEN MINERALOGY AS RELATED TO GROUND-WATER CHEMICAL CHANGES IN COAL STRIP MINING"

5. REPORT DATE
August 1978 issuing date

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Arthur Hounslow and Joan Fitzpatrick, Colorado School of Mines Research Institute; Lawrence Cerrillo and Michael Freeland, Engineering Enterprises, Inc.

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Colorado School of Mines Research Institute
Post Office Box 112
Golden, Colorado 80401

10. PROGRAM ELEMENT NO.
1NE625B

11. CONTRACT/GRANT NO.
Grant No. R-804162

12. SPONSORING AGENCY NAME AND ADDRESS
Robert S. Kerr Environmental Research Lab. - Ada, OK
Office of Research and Development
U.S. Environmental Protection Agency
Ada, Oklahoma 74820

13. TYPE OF REPORT AND PERIOD COVERED
Final (Dec. 1975 - Dec. 1977)

14. SPONSORING AGENCY CODE
EPA/600/15

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A research program was initiated to define and develop an inclusive, effective, and economical method for predicting potential ground-water quality changes resulting from the strip mining of coal in the Western United States.

To utilize the predictive method, it is necessary to sample the overburden, determine its mineralogical content, and, where applicable, to determine the quality of the ground water that may saturate the spoils. Techniques were developed for interpreting the data required to predict future ground-water quality changes. With additional research, the predictive method may also be found applicable to other types of mining operations.

Relationships among and between rock and water variables were established using factor analysis. This analysis, coupled with thermodynamic calculations, provided rational explanations of the facts observed in the study of existing mines.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Coal mining, Surface mining, Strip mining, Geology and Mineralogy	Western United States, Ground water degradation	48F

18. DISTRIBUTION STATEMENT Release to Public.	**19. SECURITY CLASS** *(This Report)* Unclassified	**21. NO. OF PAGES** 319
	20. SECURITY CLASS *(This page)* Unclassified	**22. PRICE** PC A14 MF A01

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1978-757-140/1437 Region No. 5-II

EPA-600/7-78-156
August 1978

OVERBURDEN MINERALOGY AS RELATED TO GROUND-WATER CHEMICAL CHANGES IN COAL STRIP MINING

by

Arthur Hounslow and Joan Fitzpatrick
Colorado School of Mines Research Institute
Golden, Colorado 80401

Lawrence Cerrillo and Michael Freeland
Engineering Enterprises, Inc.
Denver, Colorado 80215

Grant No. R-804162

Project Officer

Bob D. Newport
Ground Water Research Branch
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

DISCLAIMER

This report has been reviewed by the Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate, and management of pollutants in ground water; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control, or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective, and provide adequate environmental protection for the American public.

William C Galegar

William C. Galegar
Director

ABSTRACT

A research program was initiated to define and develop an inclusive, effective, and economical method for predicting potential ground-water quality changes resulting from the strip mining of coal in the Western United States.

The predictive methodology was developed from data obtained at eight mines in the Western United States. Core and cutting samples were obtained from undisturbed overburden and spoil piles, and the mineralogy and bulk chemistry of these rocks were determined. X-ray diffraction techniques were used and found to be most effective for mineralogical determinations. Water samples, both upgradient and downgradient from the spoils, were analyzed to determine the change in water composition. Standard field and laboratory analytical methods proved satisfactory to determine water composition.

Relationships among and between rock and water variables were established using factor analysis. This analysis, coupled with thermodynamic calculations, provided rational explanations of the facts observed in the study of existing mines.

Minerals found to have the greatest influence on water chemistry were carbonates, sulfates, clays, and sulfides. The natural, undisturbed bedrock water was either a sulfate or bicarbonate water with medium to low dissolved solids. Water associated with spoil piles was generally calcium-magnesium-sulfate, high-total dissolved solids waters. Water composition changes resulting from mining always included some increase in dissolved solids. Other chemical changes may also occur depending upon the mineralogy and changes in the exposure of rocks to percolating water.

To utilize the predictive method, it is necessary to sample the overburden, determine its mineralogical content, and, where applicable, to determine the quality of the ground water that may saturate the spoils. Techniques were developed for interpreting the data required to predict future ground-water quality changes. With additional research, the predictive method may also be found applicable to other types of mining operations.

This report was submitted in fulfillment of grant No. R-804162 by the Colorado School of Mines Research Institute, and Engineering Enterprises, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period December 23, 1975, to December 22, 1977.

CONTENTS

Disclaimer ii
Foreword iii
Abstract iv
Contents vii
List of Illustrations xii
List of Tables xvii
List of Abbreviations and Symbols xviii
Acknowledgments xix

1. Introduction 1
2. Conclusions 2
3. Recommendations 4
4. Previous Investigations 5
5. Regional Background 7

    Green River Coal Region 12

        Climate 12
        Geology 12
        Hydrogeology 13

    San Juan River Coal Region 13

        Climate 13
        Geology 15
        Hydrogeology 15

    Hams Fork Coal Region 17

        Climate 17
        Geology 17
        Hydrogeology 19

    Powder River Coal Region 19

        Climate 19
        Geology 20
        Hydrogeology 20

Preceding page blank

CONTENTS (Cont.)

6. Methods of Investigation 22

Field Operations 22

Site Selection 22
Drilling 23
Sampling Techniques 27

Laboratory Operations 28

Mineralogical Methods 28
Water Analysis 32

7. Mine Sites Investigated 37

Energy Fuels Mine 37

Climate 37
Geology 39
Sampling Points 39
Hydrogeology 44
Mineralogy 45
Water Chemistry 48
Input Parameters 48

Edna Mine 51

Climate 51
Geology 51
Sampling Points 52
Hydrogeology 52
Mineralogy 57
Water Chemistry 57
Input Parameters 61

McKinley Mine 61

Climate 63
Geology 63
Sampling Points 64
Hydrogeology 64
Mineralogy 70
Water Chemistry 70
Input Parameters 74

CONTENTS (Cont.)

7. Mine Sites Investigated (Cont.)

Medicine Bow Mine 74

Climate 75
Geology 75
Sampling Points 78
Hydrogeology 78
Mineralogy 83
Water Chemistry 86
Input Parameters 86

Rosebud Mine 90

Climate 90
Geology 92
Sampling Points 92
Hydrogeology 92
Mineralogy 96
Water Chemistry 96
Input Parameters 101

Kemmerer Mine 102

Climate 102
Geology 102
Sampling Points 104
Hydrogeology 104
Mineralogy 109
Water Chemistry 111
Input Parameters 111

Wyodak Mine 114

Climate 114
Geology 116
Sampling Points 116
Hydrogeology 120
Mineralogy 120
Water Chemistry 121
Input Parameters 121

CONTENTS (Cont.)

7. Mine Sites Investigated (Cont.)

Colstrip Mine 125

Climate 125
Geology 127
Sampling Points 127
Hydrogeology 127
Mineralogy 131
Water Chemistry 131
Input Parameters 135

8. Development of a Predictive Method 137

Methods of Data Interpretation 137

Factor Analysis 137
Geochemical Calculations 138
Graphical Representation of Waters 139

Geology 142

Overburden Lithology 142
Stratigraphic Continuity 142
Structure 143

Hydrogeology 143

Mineralogy 146

Calcite - $CaCO_3$ 147
Dolomite - $CaMg(CO_3)_2$ 148
Siderite - $FeCO_3$ 149
Gypsum - $CaSO_4 \cdot 2H_2O$ 149
Starkeyite - $MgSO_4 \cdot 4H_2O$ 150
Pyrite - FeS_2 151
Feldspar 151
Quartz - SiO_2 152
Clay Minerals 152
Major Clay Species 154

CONTENTS (Cont.)

8. Development of a Predictive Method (Cont.)

Water Chemistry 154

Graphical Representation of Waters 154
Vector Diagram Results 160
Factor Analysis 169
Geochemical Calculations 170

Summary of Important Chemical Reactions 172

Effects of Climate 175

9. Presentation of the Predictive Method 177

Geology and Hydrogeology 177
Climate 179
Water Chemistry 179
Mineralogy 179

References 181

Glossary of Mineral Species 185

Appendix A. Bore Hole Data and Field Logs 186

Appendix B. Whole Rock Analyses 203

Appendix C. Water Data 223

Appendix D. Geochemical Calculations 236

FIGURES

Number		Page
1	Location of mine sites investigated.	8
2	Average annual evaporation from open water surfaces in inches.	9
3	Average annual evaporation in inches.	10
4	Average annual precipitation in inches.	11
5	Coal-bearing formations in the Green River region.	14
6	Coal-bearing formations of the Gallup field, San Juan region, New Mexico	16
7	Coal-bearing formations in the Hams Fork region.	18
8	Coal-bearing formations in the Powder River region.	21
9	Typical construction for wells completed in this study.	25
10	Diagram of typical pressure-vacuum lysimeter installation.	26
11	Surface drainage in the vicinity of the Energy Fuels and Edna Mines, Colorado.	38
12	Detailed core description from Hole CD-7A. Energy Fuels Mine, Colorado.	40
13	Legend for detailed core description diagrams.	41
14	Idealized block diagram showing major geologic features. Energy Fuels Mine, Colorado	42
15	Sample location map. Energy Fuels Mine, Colorado.	43

FIGURES (Cont.)

Number		Page
16	"Vector" diagram of water compositions. Energy Fuels Mine, Colorado.	50
17	Idealized block diagram showing major geologic features. Edna Mine, Colorado.	53
18	Detailed description of core from Hole CD-1. Edna Mine, Colorado.	54
19	Sample location map. Edna Mine, Colorado.	55
20	Individual watersheds on the Edna Mine spoils, and discharge monitoring stations used by McWhorter.	56
21	"Vector" diagram of water compositions. Edna Mine, Colorado.	60
22	Surface drainage in the vicinity of the McKinley Mine, New Mexico.	62
23	Idealized block diagram showing major geologic features. McKinley Mine, New Mexico.	65
24	Detailed description of core from Hole EMK-1. McKinley Mine, New Mexico.	66
25	Detailed description of core from Hole EMK-6C. McKinley Mine, New Mexico.	67
26	Detailed description of core from Hole EMK-11. McKinley Mine, New Mexico.	68
27	Sample location map. McKinley Mine, New Mexico.	69
28	"Vector" diagram of water compositions. McKinley Mine, New Mexico.	72
29	Surface drainage in the vicinity of the Medicine Bow Area, Wyoming.	76

FIGURES (Cont.)

Number		Page
30	Idealized block diagram showing major geologic features. Medicine Bow Mine, Wyoming.	77
31	Detailed description of core from Hole 33-11-1. Medicine Bow Mine, Wyoming.	79
32	Detailed description of core from Hole 33-4-2. Medicine Bow Mine, Wyoming.	80
33	Sample location map. Medicine Bow Mine, Wyoming.	82
34	Water production versus depth. Medicine Bow Mine, Wyoming.	84
35	"Vector" diagram of water compositions. Medicine Bow Mine, Wyoming.	88
36	"Vector" diagrams of water compositions. Medicine Bow Mine, Wyoming.	89
37	Surface Drainage in the vicinity of the Rosebud Mine, Wyoming.	91
38	Detailed description of core from Hole 3R4S-15-1. Rosebud Mine, Wyoming.	93
39	Sample location map. Rosebud Mine, Wyoming.	94
40	Idealized block diagram showing major geologic features. Rosebud Mine, Wyoming.	95
41	Water production versus depth during drilling. Rosebud Mine, Wyoming.	97
42	"Vector" diagram of water compositions. Rosebud Mine, Wyoming.	99
43	Surface drainage in the vicinity of the Kemmerer Mine, Wyoming.	103
44	Idealized block diagram showing major geologic features. Kemmerer Mine, Wyoming.	105

FIGURES (Cont.)

Number Page

45 Detailed description of core from Hole KCW-4-1. Kemmerer Mine, Wyoming. 106

46 Sample location map. Kemmerer Mine, Wyoming. 108

47 "Vector" diagram of water compositions. Kemmerer Mine, Wyoming. 112

48 Surface drainage in the vicinity of the Wyodak Mine Area, Wyoming. 115

49 Idealized block diagram showing major geologic features. Wyodak Mine, Wyoming. 117

50 Sample location map. Wyodak Mine, Wyoming. 118

51 Description of overburden materials. Wyodak Mine, Wyoming. 119

52 "Vector" diagram of water compositions. Wyodak Mine, Wyoming. 123

53 Surface drainage in the vicinity of the Colstrip Mine Area, Montana. 126

54 Idealized block diagram showing major geologic features. Colstrip Mine, Montana. 128

55 Composite overburden stratigraphy, Areas D & E. Colstrip Mine, Montana 129

56 Sample location map. Colstrip Mine, Montana. 130

57 "Vector" diagram of water compositions. Colstrip Mine, Montana. 133

58 Derivation of a five-component vector diagram from a five-component bar graph. 141

59 Ground-water overburden relationships. 144

FIGURES (Cont.)

Number		Page
60	Water genesis in terms of three end-member types at the Energy Fuels and Edna Mines, Colorado.	158
61	"Vector" diagram of water compositions. Energy Fuels Mine, Colorado.	161
62	"Vector" diagram of water compositions. Edna Mine, Colorado.	162
63	"Vector" diagram of water compositions. McKinley Mine, New Mexico.	163
64	"Vector" diagram of water compositions. Medicine Bow Mine, Wyoming.	164
65	"Vector" diagram of water compositions. Rosebud Mine, Wyoming.	165
66	"Vector" diagram of water compositions. Kemmerer Mine, Wyoming.	166
67	"Vector" diagram of water compositions. Wyodak Mine, Wyoming.	167
68	"Vector" diagram of water compositions. Colstrip Mine, Montana.	168
69	Aerobic reaction cycle: weathering of minerals in the presence of H_2O, CO_2, and O_2.	173
70	Anerobic reaction cycle: anerobic reactions influenced predominantly by sulfate reduction; i. e., the oxidation of organic matter using the oxygen tied up in the sulfate. Microbial catalysis is a necessity.	174
71	Predictive method flow chart.	178

TABLES

Number		Page
1	Field Analytical Methods	29
2	Laboratory Analytical Methods	33
3	Reproducibility of Analyses, Kemmerer Mine, Wyoming	35
4	X-ray Diffraction Data, Energy Fuels Mine, Colorado	46
5	Water Data, Energy Fuels Mine, Colorado	49
6	X-ray Diffraction Data, Edna Mine, Colorado	58
7	Water Data, Edna Mine, Colorado	59
8	X-ray Diffraction Data, McKinley Mine, New Mexico	71
9	Water Data, McKinley Mine, New Mexico	73
10	X-ray Diffraction Data, Medicine Bow Mine, Wyoming	85
11	Water Data, Medicine Bow Mine, Wyoming	87
12	X-ray Diffraction Data, Rosebud Mine, Wyoming	98
13	Water Data, Rosebud Mine, Wyoming	100
14	X-ray Diffraction Data, Kemmerer Mine, Wyoming	110
15	Water Data, Kemmerer Mine, Wyoming	113
16	X-ray Diffraction Data, Wyodak Mine, Wyoming	122
17	Water Data, Wyodak Mine, Wyoming	124
18	X-ray Diffraction Data, Colstrip Mine, Montana	132
19	Water Data, Colstrip Mine, Montana	134
20	Analyses Calculated to 100 Milliequivalents Per Liter Cations	155
21	All Analyses Recalculated to 100 Milliequivalents Per Liter Cations	157

LIST OF ABBREVIATIONS AND SYMBOLS

Å	angstrom, 10^{-10} meter
CEC	cation exchange capacity
TDS	total dissolved solids (in mg/l)
mg/l	milligrams per liter
meq/l	milliequivalents per liter
ppm	parts per million
μm	microns
μ	ionic strength
Eh	oxidation-reduction potential
sp gr	specific gravity
°F	degrees Farenheit
°C	degrees Centigrade
OD	outside diameter
BLS	below land surface
PVC	polyvinyl chloride
gpm	gallons per minute
ΔG_r	change in free energy of reaction (in kilocalories)
AWWA	American Water Works Association
APHA	American Public Health Association
WPCF	Water Pollution Control Federation
pt	pint
qt	quart
gal	gallon
ml	milliliter
g	gram
hr	hour

ACKNOWLEDGMENT

We wish to acknowledge the cooperation and assistance of the Energy Fuels Corporation, the Pittsburg and Midway Coal Co., the Medicine Bow Coal Co., the Rosebud Coal Sales Co., Peter Kiewit and Sons Co., the Kemmerer Coal Co., the Wyodak Resources Development Corp., and the Western Energy Co.

In addition, we gratefully acknowledge contributions and criticisms of persons too numerous to mention individually from the United States Geological Survey, the Environmental Protection Agency, and the United States Bureau of Mines.

We especially wish to acknowledge the contribution of Mr. Bob Newport from the Environmental Protection Agency, Ada, Oklahoma. As project officer, his continued support and assistance have proved invaluable to this research project.

SECTION 1

INTRODUCTION

The impending widespread strip mining of coal in the semi-arid Western United States is of concern to the Environmental Protection Agency because of the uncertain effects of mining on ground-water quality. Protecting ground-water quality is of vital importance to the present and future economy of that section of the United States. As a consequence of this, an increasing number of environmental regulations have imposed a restraint on present and future strip mine operations. One problem faced by the mine operator is that of predicting, prior to mining, the effect that mining will have on ground-water quality. Historically, these predictions have been made using several different methods. For example, premining hydrologic studies showed the surface water conditions, ground-water flow direction, and existing quality; soil extract tests on sections of the overburden indicated that certain leachable chemical species were present; and plant growth tests provided additional information on chosen sections of the overburden column.

In an effort to protect ground-water quality and ameliorate the compliance problems faced by miners, the Environmental Protection Agency initiated a program to study ground-water degradation as a result of strip mining of coal. The overall objective of the program was to define an inclusive, effective, and economic method for predicting potential ground-water quality changes based on a detailed examination of overburden mineralogy correlated with water chemistry at existing mines. Eight coal mining areas throughout the Western United States were selected for study. Samples of ground water from these mines were obtained upgradient and downgradient from the spoil pile, and core samples were obtained from the undisturbed overburden. Ground-water composition before and after passage through the spoil piles was correlated with the results of the mineralogical examination of the overburden samples.

This report presents a method for predicting the post-mining chemical changes that may occur in ground-water quality based upon a premining examination of the overburden column.

SECTION 2

CONCLUSIONS

It is possible to predict the changes in the quality of ground water in coal strip mines in the Western United States by a study of overburden mineralogy and hydrology.

A certain minimal amount of field and laboratory effort is required for the successful utilization of the predictive method outlined in this study. This includes drilling, coring, and completing a small number of holes in order to define the ground-water characteristics and to obtain the necessary rock and water samples for analyses. The mineralogy of the overburden is best determined by a combination of core logging techniques and x-ray diffraction. Water composition is determined by the use of a combination of conventional field and laboratory methods.

In those locations where the proposed mine will be located above the water table, the predictive method can be applied using only overburden samples obtained from exploratory cores or from presently existing adjacent high walls. Where the proposed mine will be below the water table, it will be necessary to obtain samples of the ground water.

Minerals having the greatest influence on water chemistry were found to be carbonates, sulfates, clays, and sulfides. The carbonate-sulfate ratio controls the pH. Magnesium enrichment in the water may result because of gypsum precipitation. Heavy metals are generally absent from the waters due to the adsorption by clays.

Water analyses show that calcium, magnesium, sodium, bicarbonate, and sulfate generally comprise over 98% of the total ions in solution in both surface and ground waters. Spoil waters are generally calcium-magnesium-sulfate waters, high in total dissolved solids (TDS). Ground water occurring in association with undisturbed overburden sandstones are generally low in TDS and have a mixed-cation-bicarbonate composition. Ground waters occurring in association with undisturbed overburden shales and unmined coal seams usually have a calcium-magnesium-sulfate composition and an intermediate TDS content.

In geologic environments in which the vertical and horizontal permeability of the overburden are of near-equal magnitude, and water contacts a representative portion of the overburden, the change in ground-water quality after mining will be minimized. However, where water cannot contact a representative section of the overburden, the change in ground-water quality after mining may be marked.

SECTION 3

RECOMMENDATIONS

This research program provided a method to predict potential ground-water changes resulting from coal strip mining in the semi-arid Western United States. Increasing demands made upon the already limited quantity of water dictate that related research must be continued.

Seminars should be held for Western coal strip mine operators where this predictive method can be explained. These seminars will provide the technology transfer in a timely and direct manner, and thus insure that the results of this research are utilized.

Other potential applications of this method need to be researched. This method may be applicable to underground coal gasification, uranium mining, Eastern coal strip mining, oil shale -- both in situ and strip mining -- and metals mining.

SECTION 4

PREVIOUS INVESTIGATIONS

A vast number and variety of approaches exist in the study of ground-water chemical changes resulting from coal mines. The majority of studies have been directed toward the effects on soils or surface waters, and toward the causes and solution of acid mine drainage problems. Gleason and Russell (1) have prepared an annotated bibliography spanning the period from 1910 to 1976 on this subject. In a review of these abstracts, and of papers referenced in other sources, none addressed the problem in a manner similar to the approach taken for this investigation. Based on the literature, one can arrive at some basic premises: namely, that most mine-contact waters are higher in TDS; that sulfides in one form or another are the basic cause of most acid mine problems; and that the availability of carbonates plays an important role in the resultant water chemistry. Obviously, these three factors present an over-simplification of a serious problem. The literature indicates the need for developing a predictive method useful in the generally nonacid drainage environments of the west.

Two papers that address a predictive approach to some degree are those by Caruccio (2) and by McWhorter (3). Caruccio evaluated the distribution of the grain size of pyrite in the mine strata and the chemical composition of existing ground waters. From such evaluations, he made predictions of the areas, in bituminous coal fields of Pennsylvania, that would yield "...(1) highly acid-high sulfate mine drainages, (2) moderately acid-moderate sulfate mine drainages, (3) neutral mine drainages..." Caruccio's work was based on laboratory leaching tests of some very specific parameters, and therefore differs considerably from the research conducted for this study. This study relied heavily on interpretation of natural processes, including microbilogical.

McWhorter's research, based on data from one of the mines used in this investigation, was primarily directed toward changes in surface water runoff that would occur as a result of flow over undisturbed versus disturbed materials. On the basis of water budgets and water chemistry from specific watersheds, McWhorter developed an algebraic model to estimate the influence of surface mining on the chemistry of receiving waters. His work was thus directed primarily toward overland runoff, and to a lesser degree toward the shallow, 5-ft, partially saturated zone. The work conducted during this investigation was directed toward ground water in the saturated or water table zone, and toward deeper interburden aquifers.

SECTION 5

REGIONAL BACKGROUND

The mines investigated for this report are all located in the semi-arid Rocky Mountain region in the states of New Mexico, Colorado, Wyoming, and Montana (see Figure 1). Deposits in this region contain 56% of the coal reserves of the United States, as determined by mapping and exploration up to 1967 (4). The mine sites investigated can, therefore, be considered as representative of "western coals." The general aspects of each coal region within the Rocky Mountain region will be discussed in this section. These regions, identified by Averitt in the Geologic Atlas of the Rocky Mountain Region (see Figure 1), essentially coincide with the major structural basins of the Rocky Mountain region and include:

Green River region
San Juan River region
Hams Fork region
Powder River region.

The coal deposits investigated are all of Late Cretaceous Age except for the Hanna Basin mines which are Tertiary and the mines in the Kemmerer Field which encompass both Cretaceous and Tertiary coals. These coal deposits were laid down along margins of the Cretaceous depositional basins in freshwater swamp areas (5). The thickness and continuity of deposits were dependent upon structural activities and advancing and retreating shorelines. The Cretaceous Formations are all of the Mesaverde Group or of equivalent age. The Tertiary coals investigated are from the Tongue River Member of the Fort Union Formation. All coals investigated are of subbituminous or bituminous rank.

A brief discussion of the climate, geology, and hydrogeology of these regions is presented in this section. The information available for each region varies; therefore, some descriptions will appear more detailed than others. Maps that show climatic conditions are presented to provide background information for the regions to be discussed (see Figures 2 through 4).

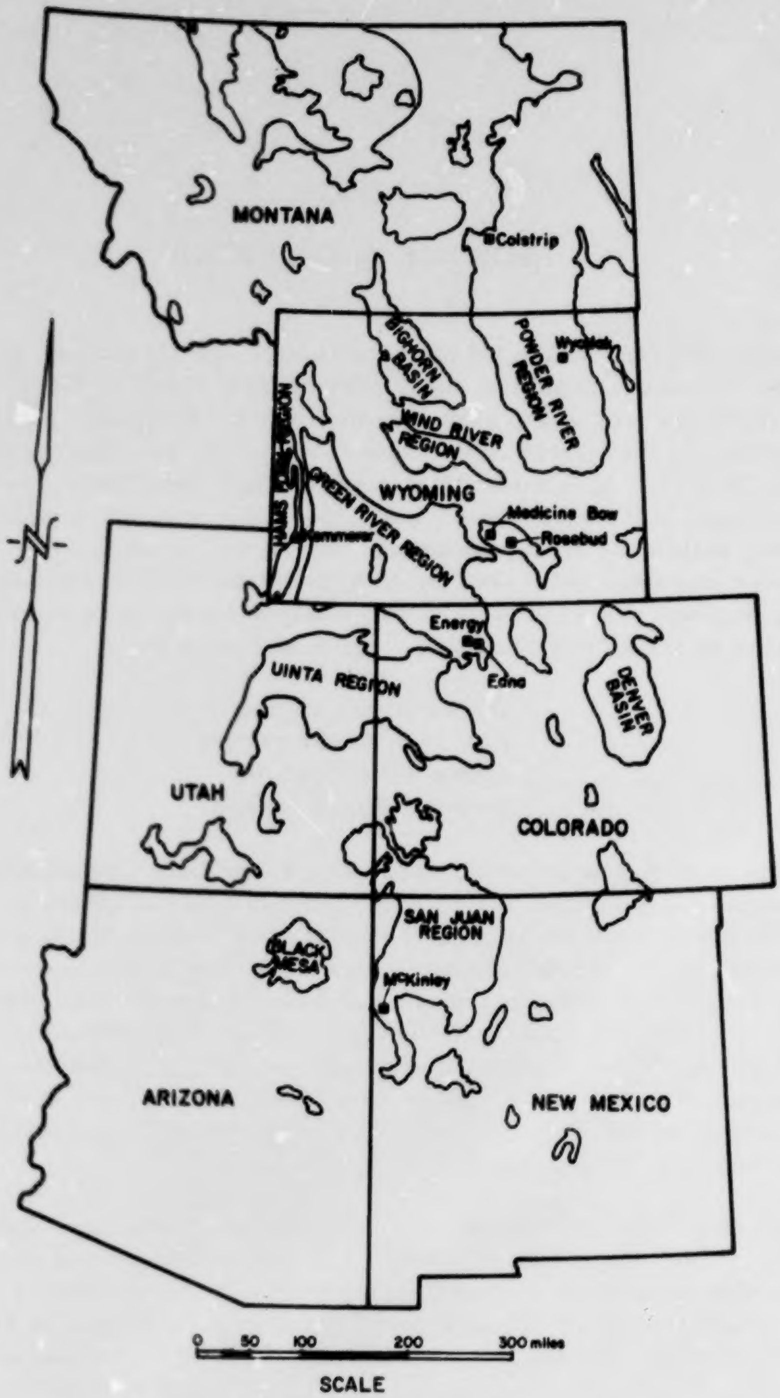

MONTANA
Colstrip
BIGHORN BASIN
POWDER RIVER REGION
Wyodak
WIND RIVER REGION
WYOMING
GREEN RIVER REGION
Kemmerer
Medicine Bow
Rosebud
Energy
Edna
UINTA REGION
DENVER BASIN
UTAH
COLORADO
SAN JUAN REGION
BLACK MESA
McKinley
ARIZONA
NEW MEXICO
0
50
100
200
300 miles
SCALE

Figure 1. Location of mine sites investigated. (Base map after Averitt) (4)

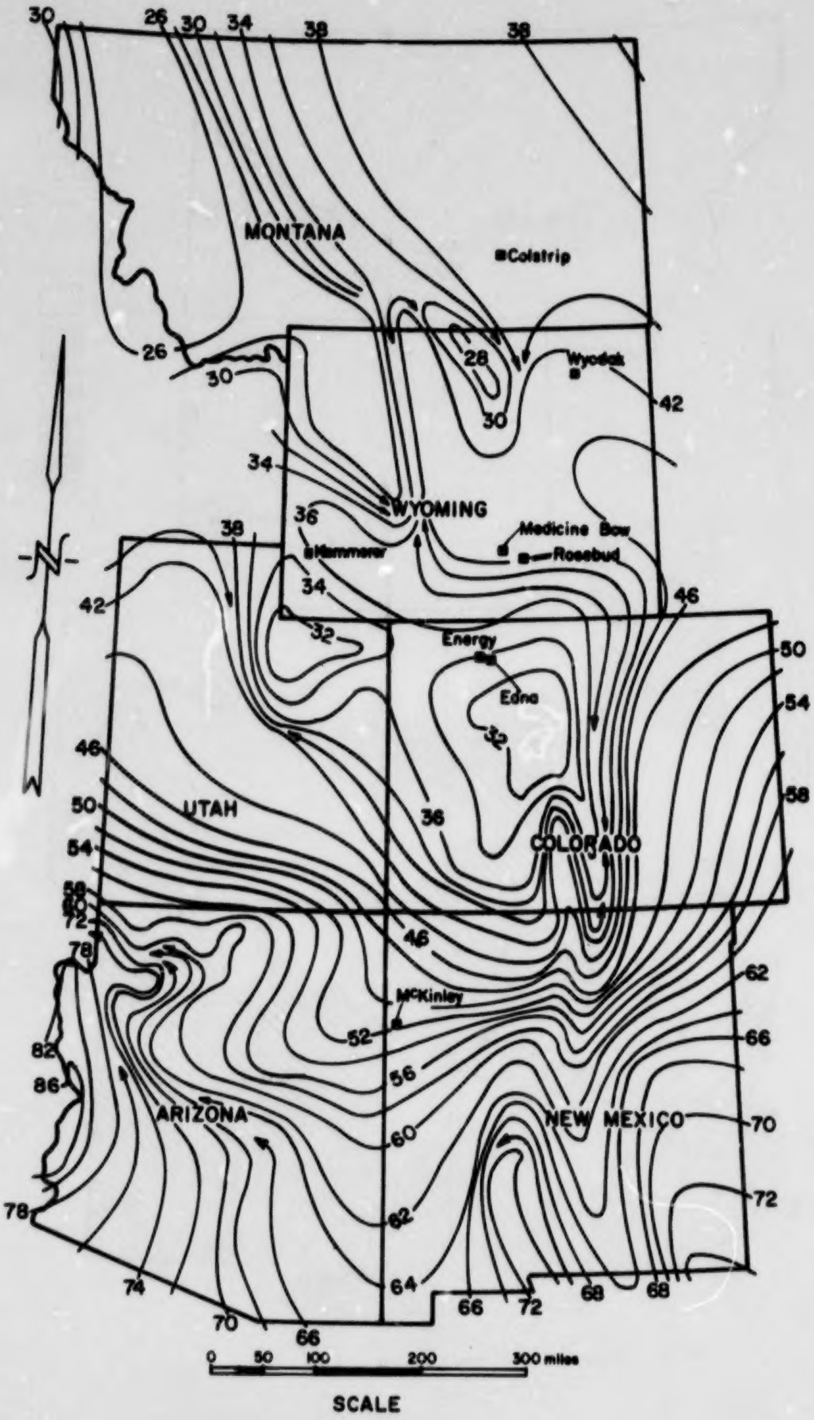

MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
Colstrip
Wyodak
Medicine Bow
Rosebud
Kemmerer
Energy
Edna
McKinley
30
26
30
34
38
38
26
30
28
30
42
34
36
38
34
42
32
32
46
50
54
58
60
72
78
82
86
78
74
70
66
36
46
46
50
54
58
62
66
70
72
52
56
60
62
64
66
72
68
68
0
50
100
200
300 miles
SCALE

Figure 2. Average annual evaporation from open water surfaces in inches. (modified from Geraghty, et al.) (41)

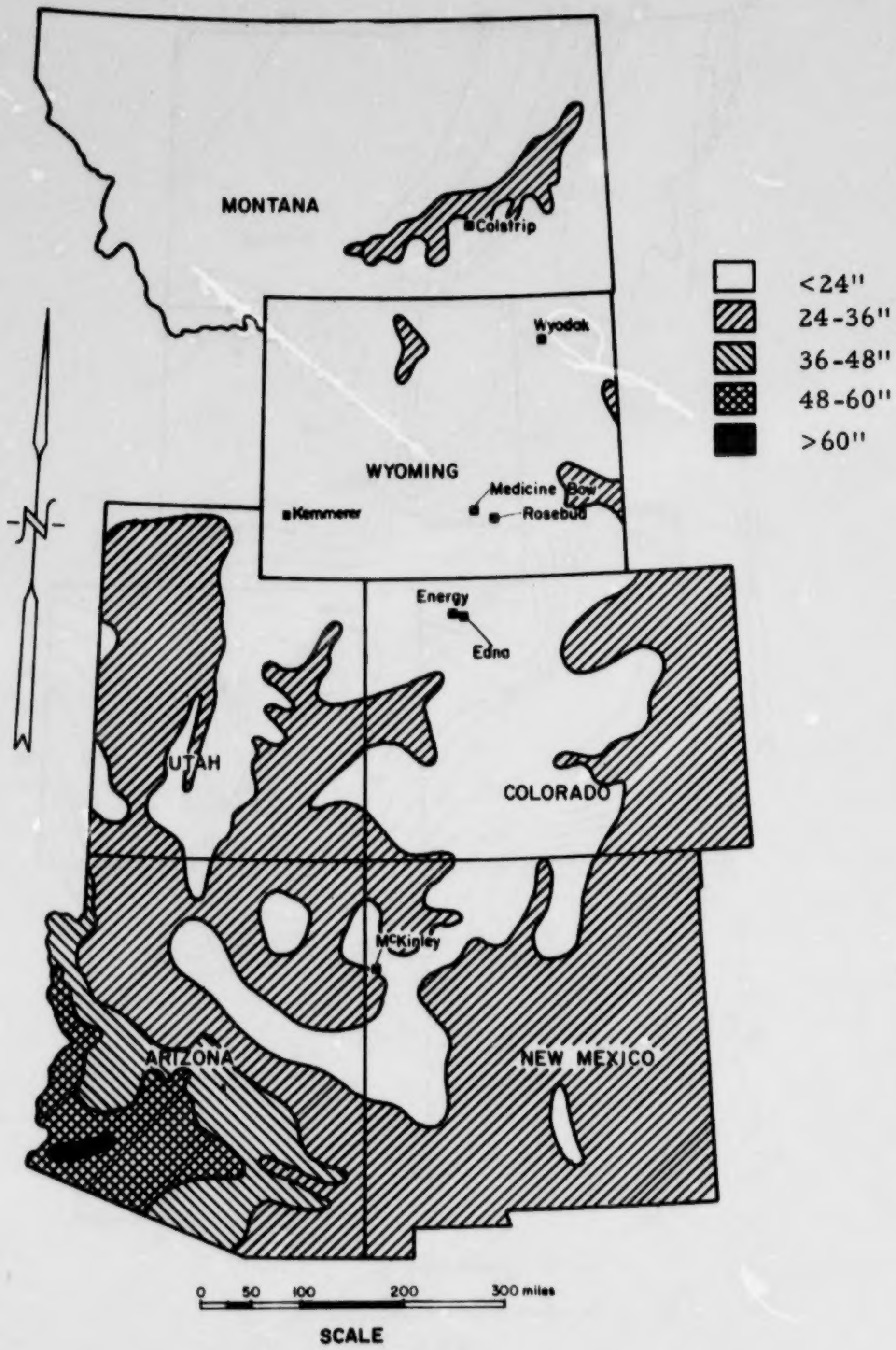

MONTANA
Colstrip
Wyodak
WYOMING
Medicine Bow
Rosebud
Kemmerer
N
Energy
Edna
UTAH
COLORADO
McKinley
ARIZONA
NEW MEXICO
<24"
24-36"
36-48"
48-60"
>60"
0
50
100
200
300 miles
SCALE

Figure 3. Average annual evaporation in inches. (modified from Geraghty, et al.) (41)

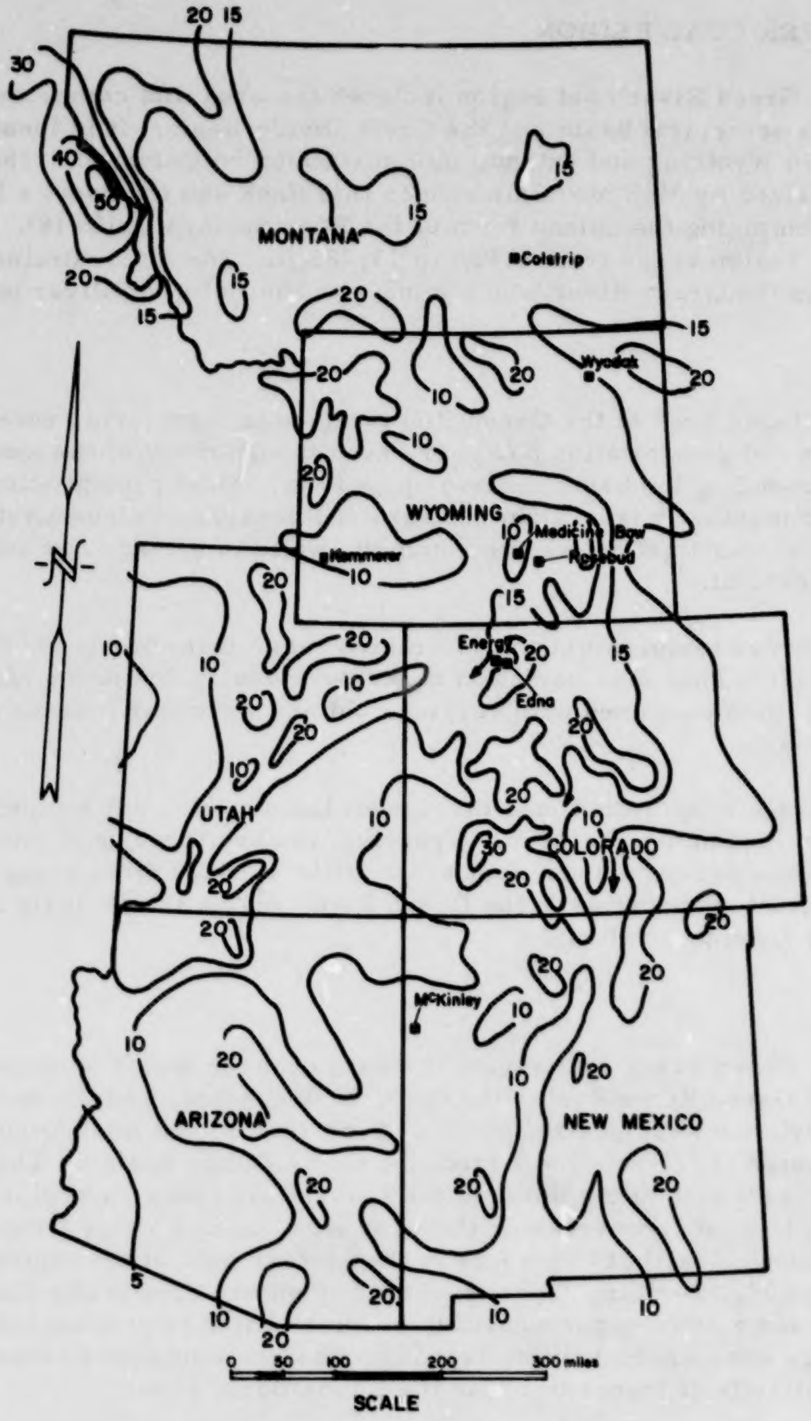

MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
Colstrip
Wyodak
Kemmerer
Medicine Bow
Rosebud
Energy
Edna
McKinley
20
15
30
40
50
10
5
0
50
100
200
300 miles
SCALE

Figure 4. Average annual precipitation in inches. (modified from Geraghty, et al.) (41)

GREEN RIVER COAL REGION

The Green River coal region includes the area that comprises the Green River structural basin and the Great Divide Basin. It is located in southwestern Wyoming and extends into northwestern Colorado. The region is characterized by high mountain ranges that flank and intersect a high plateau area containing the upland form of the Rock Springs Uplift (6). Elevations in the region range from 6,050 to 13,785 ft. The major drainage from the region is the Green River which joins with the Colorado River in Utah.

Climate

The basin area of the Green River region is semi-arid, receiving as little as 6 in. of precipitation per year, even though many of the mountain ranges surrounding the basin receive up to 40 in. Most precipitation during the summer months is from light showers and occasional cloudbursts. During fall and winter light snows are common, while in spring, wet snows and rain are prevalent.

Recorded temperatures in the region range from minus 55°F to a plus 107°F (7). This wide variation in temperature is due to the high elevation of the region combined with varying cold and warm air masses that invade the area.

Average evaporation rate throughout the state for a 5-mo period, May through September, is 41 in. Freezing weather throughout much of the remaining time prevents consistent evaporation records from being made (8). The actual evaporation in the Green River region is not likely to differ appreciably from this value.

Geology

The Green River coal region consists of three major structural basins: the Green River Basin, the Great Divide Basin, and the Hanna Basin. Through the south-central portion of the region, the Rock Springs uplift separates the Green River from the Great Divide basins. The formations on the east side of the uplift in the Cretaceous rocks have dips that range from 4° to 10°, whereas on the west side the dips range from 6° to 2° (9). Cretaceous coal-bearing rocks in the eastern part of the region dip from 20° to 60°. Tertiary deposits in the region are essentially flat-lying. Faulting is not extensive throughout the region, but it is pronounced in the Rock Springs area where faulting trends northeast-southwest across the uplift. Similar fault trends occur in the Hanna Basin area.

"Coals in the Green River Region occur in the Mesaverde Group and in the Lance Formation, both of Upper Cretaceous Age; in the Fort Union

Formation, of Paleocene Age; and in the Wasatch Formation, of Eocene Age." (8). Figure 5 shows the principal coal-bearing rocks in the Green River region. The Fort Union and the Wasatch Formations are the most widespread coal-bearing rocks throughout the Green River coal region. These coals are generally of subbituminous rank.

Hydrogeology

The Green River, Wasatch, Fort Union, and older formations which underlie most of the region contain water under artesian conditions. The depth to water is generally less than 200 ft, but the artesian aquifers in the deeper part of the basin lie at depths exceeding 1,000 ft. Well yields range from 10 to 100 gpm (10).

The Mesaverde Group of Cretaceous Age, the thickest major aquifer, ranges in thickness from 1,500 to 5,300 ft. Some wells reportedly yield up to 1,000 gpm, but most yield less than 600 gpm. Dissolved solids range from 300 to 2,500 mg/l.

SAN JUAN RIVER COAL REGION

The San Juan River coal region extends from southwestern Colorado into northwestern New Mexico. This area essentially coincides with the San Juan River Basin which is a major physiographic subdivision of the Colorado Plateau.

The region is characterized by mesas, rolling plains, badlands, and sharp canyons. Land surface elevations vary from approximately 5,000 ft along the San Juan River to peaks in the San Juan Mountains that are above 13,000 ft (11).

Drainage from the basin is primarily by the San Juan River and its tributaries in the north and northwestern part of the basin. Other major drainages include the Animas River, Mancos River, and McElmo Creek.

Climate

Semi-arid to arid conditions exist throughout much of the region. Average January temperature ranges from 26° to 30°F, and average July temperature ranges from 20° to 74°F (11). Annual precipitation is less than 10 in., but may range upward to 20 in. in areas of higher elevation. Precipitation during summer months is a result of brief, but often intense thunderstorms. Winter precipitation is caused principally by frontal activity from Pacific storms and, therefore, tends to be sparse.

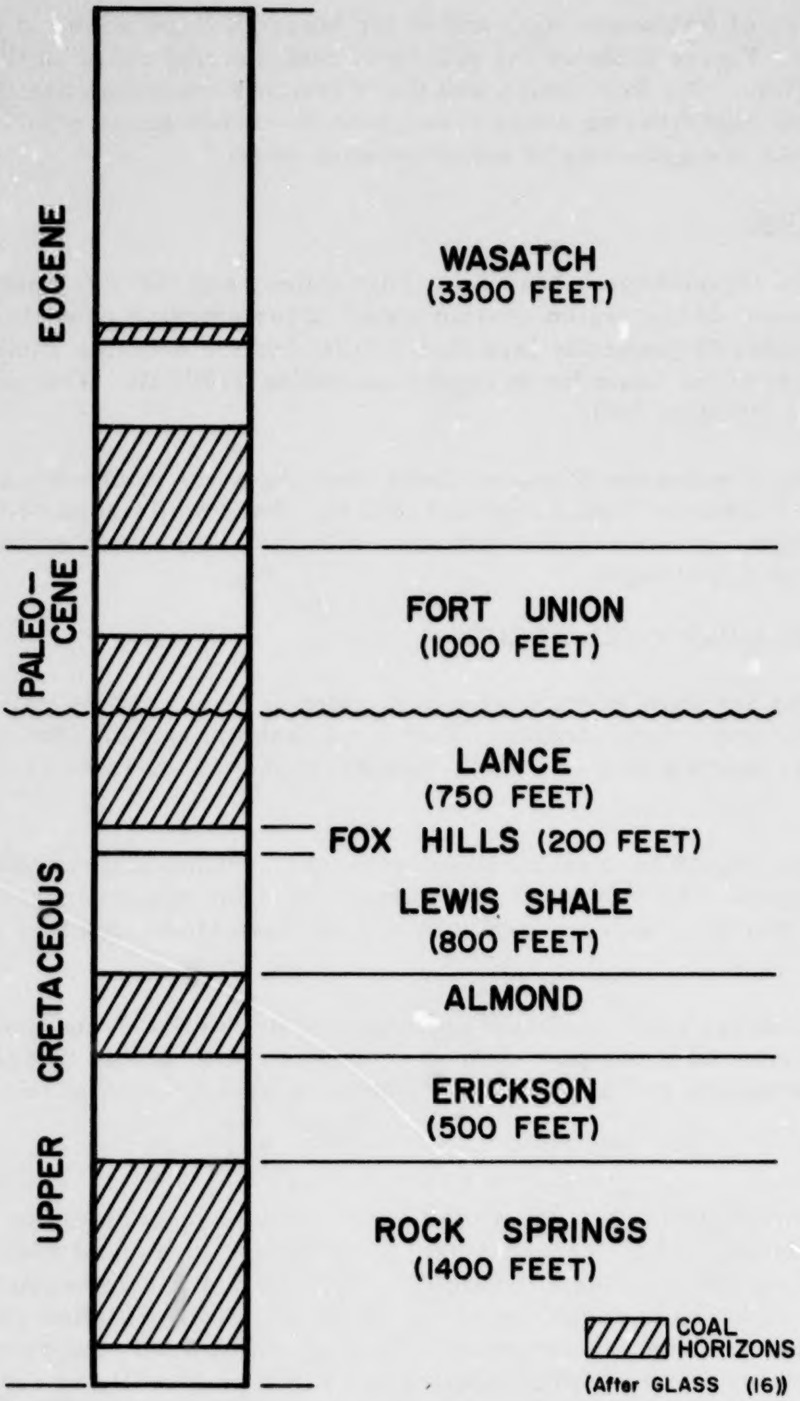

EOCENE
PALEO-CENE
UPPER CRETACEOUS
WASATCH (3300 FEET)
FORT UNION (1000 FEET)
LANCE (750 FEET)
FOX HILLS (200 FEET)
LEWIS SHALE (800 FEET)
ALMOND
ERICKSON (500 FEET)
ROCK SPRINGS (1400 FEET)
COAL HORIZONS
(After GLASS (16))

Figure 5. Coal-bearing formations in the Green River region.

Potential evaporation is much greater than average annual precipitation throughout the state, and is not expected to differ in this region. Values range from 23 to 41 in. from southeastern valleys to the north-central mountains, respectively.

Geology

The San Juan coal region is essentially coincident with the San Juan Basin which is a part of the Colorado physiographic province. Strata in the central part of the basin are almost horizontal. Structure to the east, adjacent to the Naciemento uplift, causes beds on the east to dip steeply to the west. Strata in the western side of the basin dip gently to the east as a result of the Defiance uplift located between the San Juan Basin and the Black Mesa Basin in northeastern Arizona.

Another structural feature worthy of mention is the Gallup-Zuni syncline, or Gallup Sag, that extends southward from the southwestern corner of the San Juan Basin. This feature, combined with the Zuni uplift and Nutria monocline along the southern border of the basin, creates a structurally complex area.

As is the case throughout the Rocky Mountain region, the coals are primarily of Cretaceous origin. In this region the coal-bearing units (Figure 6) are included in the Lower and Upper Cretaceous Dakota Sandstone, the Upper Cretaceous Dilco and Gibson Members of the Crevasse Canyon Formation, and the Fruitland Formation (12).

Hydrogeology

Although scarce, the ground-water found in the San Juan Basin represents the largest remaining water supply available to New Mexico (13). The value of these waters was emphasized by Special Order 124 on July 29, 1976, by the State Engineer "....declaring the San Juan Basin an underground water basin." (14).

Two of the major potential aquifers appear to be the Gallup Sandstone of Late Cretaceous Age and the Westwater Canyon Sandstone Member of Jurasic Age. The Gallup Sandstone is 130- to 170-ft thick and has a transmissivity of about 120 ft^2/day. The Westwater Canyon Sandstone Member is highly variable in composition. It consists of fine-to-coarse-grained sandstones that range from low to relatively high permeability. Transmissivity values for wells completed in this formation range from 267 to 401 ft^2/day.

Water quality in the Gallup Sandstone is only fair, about 1,800 mg/l total dissolved solids, and that in the Westwater Canyon is fair-to-poor,

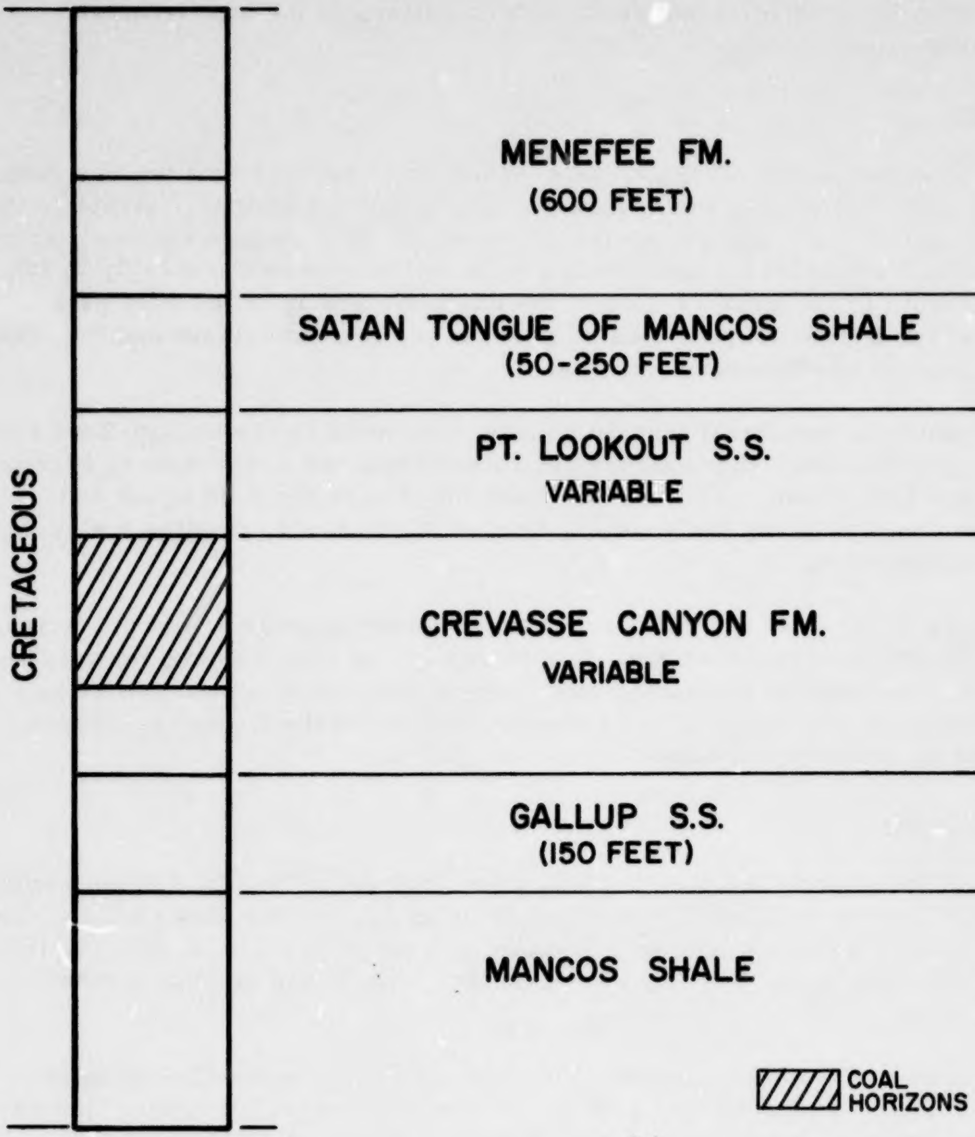

MENEFEE FM.
(600 FEET)
SATAN TONGUE OF MANCOS SHALE
(50-250 FEET)
PT. LOOKOUT S.S.
VARIABLE
CREVASSE CANYON FM.
VARIABLE
GALLUP S.S.
(150 FEET)
MANCOS SHALE
CRETACEOUS
COAL HORIZONS

Figure 6. Coal-bearing formations of the Gallup field, San Juan region, New Mexico. (11)

having total dissolved solids ranging from 1,000 to 5,000 mg/l. Waters in several other sandstone units throughout the basin are too saline for most uses (14).

HAMS FORK COAL REGION

The Hams Fork coal region occupies that part of southwestern Wyoming known as the Thrust Belt. It is an elongated, nearly rectangular area that lies within the Middle Rocky Mountain physiographic province. Elevations range from 5,600 ft to peaks in excess of 10,000 ft (Figure 1).

Although relatively small in area, 5,300 mi^2, three major drainage basins originate here: Snake, Bear, and Green Rivers (15).

Climate

Because of the variable topography, the climatic conditions throughout this area are somewhat irregular. Although semi-arid, with average annual precipitation of 9 in. at Kemmerer and Sage, precipitation greater than 40 in. occurs in the mountain ranges to the north (15). Most precipitation is in the form of showers and thunderstorms in the spring and summer, except for the higher elevations where most precipitation occurs as snow. Average annual potential evaporation exceeds precipitation (Figures 2 and 3). The mean maximum temperature is approximately 26°F, and the mean minimum temperature is approximately 0°F.

Geology

Of all the areas investigated, the Hams Fork coal region is structurally the most complex. The basement materials are comprised of Precambrian igneous and metamorphic rocks which are overlain by 55,000 ft of Paleozoic and Mesozoic rocks (15). Thrust faults abound, but the rock units are unmetamorphosed, and major fault zones show no breccia or gouge material. Some of the larger thrusts have stratigraphic displacements that range from 20,000 to 40,000 ft. These folded Paleozoic and Mesozoic rocks thrust eastward over folded Cretaceous rocks (16).

The coal-bearing rocks of the region, Bear River, Frontier, and Adaville Formations, crop out in long narrow belts bounded by thrust faults on the flanks of eroded folds. Of these Cretaceous coals, the Adaville is the most important coal-bearing formation (see Figure 7). More than 32 coal seams that range in thickness from 10 to 110 ft occur within a 1,000-ft interval of this formation. The coals in this region tend to be highly variable in thickness as a result of splitting and coalescing.

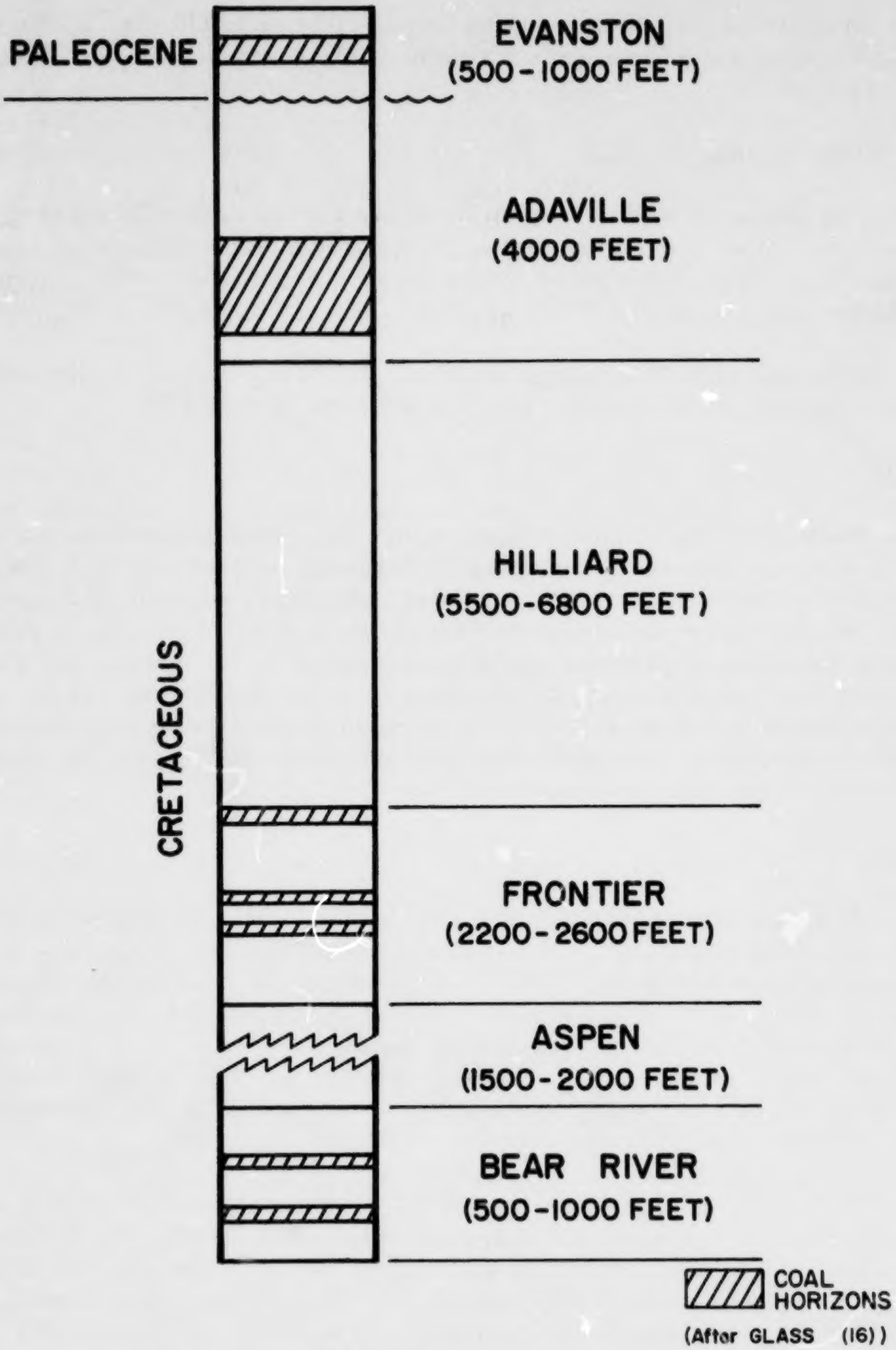

PALEOCENE
EVANSTON
(500 - 1000 FEET)
ADAVILLE
(4000 FEET)
HILLIARD
(5500-6800 FEET)
CRETACEOUS
FRONTIER
(2200 - 2600 FEET)
ASPEN
(1500 - 2000 FEET)
BEAR RIVER
(500 - 1000 FEET)
COAL HORIZONS
(After GLASS (16))

Figure 7. Coal-bearing formations in the Hams Fork region.

Hydrogeology

In most regions, recharge is primarily a result of direct penetration of precipitation and snowmelt. However, in some areas of the Hams Fork region, one unit may be recharging another because of contact along a fault zone. In fact, one unit may be receiving recharge in one basin and discharging in another basin. Most discharge in the region is through large springs which, combined with interbasin movement, cause high runoff at some surface gaging stations (15). In general, the ground-water movement reflects the surface water drainage.

POWDER RIVER COAL REGION

The Powder River coal region is a large tongue-shaped area that includes the structural Powder River Basin. It is located in northeastern Wyoming and extends northward into Montana. It is bounded on the west by the Big Horn Mountains, on the east by the Black Hills uplift, and on the north by the Laramie Range and Hartville uplift. If the elevations of the bordering Big Horn Mountains are considered, the range of elevations in the region would be 3,100 to 13,000 ft. Rugged uplands, wide rolling valleys, and badlands characterize the basin topography.

Major drainages from the region include the Powder, Belle Fourche, and Cheyenne Rivers and their tributaries. Drainage is north-northeast through the basin.

Climate

The climate of the Powder River coal region can be regarded as semi-arid. The Big Horn Mountains to the west and the Black Hills uplift to the east receive considerably more precipitation than the basin proper.

The mean annual precipitation in the region is 12 to 14 in., whereas the Black Hills receive up to 20 in. and the Big Horns in excess of 40 in. (17). Most precipitation is from wet spring snows and rain.

Temperature ranges vary widely both daily and annually. The Gillette station recorded average monthly temperature of 10°F in January to 88°F in July. The high potential evaporation which exceeds average annual precipitation is a result of strong winds over the area as much as a result of low precipitation. Average wind velocity throughout the year is 13 mph; however, winds of 30 to 40 mph may persist for a few days.

Geology

The structural Powder River Basin formed during the Laramide Orogeny (9). This asymmetric basin has its deepest portion in the west, adjacent to the Big Horn Mountains and approximately parallel with them. The highly deformed western side of the basin has dips from 30° eastward to near vertical (18). Rocks along the eastern portion of the basin dip gently 3° to 5° basinward at most places. Sediments ranging in age from Cambrian to Holocene make up approximately 18,000 ft of strata in the deeper areas of the basin. Faults are not prevalent in the region, however, some are present in the western and northern portions of the basin.

It is estimated that more than one-half of the coals of Wyoming occur within the Fort Union and Wasatch Formations (Figure 8). Coal thicknesses of 50 to 100 ft occur in the Fort Union Formation. The Wyodak-Anderson (W-A) coal in this formation is "....one of the world's largest known coal deposits." (19). Although beds dip 3° to 5° westward along the eastern margin of the region, rock layers in the W-A coal seam area have an average incline of less than 1° (19).

Hydrogeology

Data on observation wells in this region indicate that a balance exists between recharge and discharge of ground water (18). Recharge to younger, Cenozoic, rocks is basically from penetration of precipitation, whereas recharge to older, Mesozoic and Paleozoic, rocks is from precipitation in addition to stream infiltration where streams traverse outcrops of these rocks. Irrigation may play a minor role in recharge of some units, but would have the most effect on alluvial materials. Springs, lakes, pumpage from wells, and evapotranspiration all constitute means of ground-water discharge.

Based on the work done in the Gillette area by the U. S. Geological Survey, ground-water movement is shown to be from west to east, and ultimately to the north (20). This movement is in the opposite direction from the dip in the area and is attributable to the greater amount of recharge and greater amount of outcrop exposure in the area west of the strippable coal deposits. Yields from wells throughout the region range from 10 to 100 gpm.

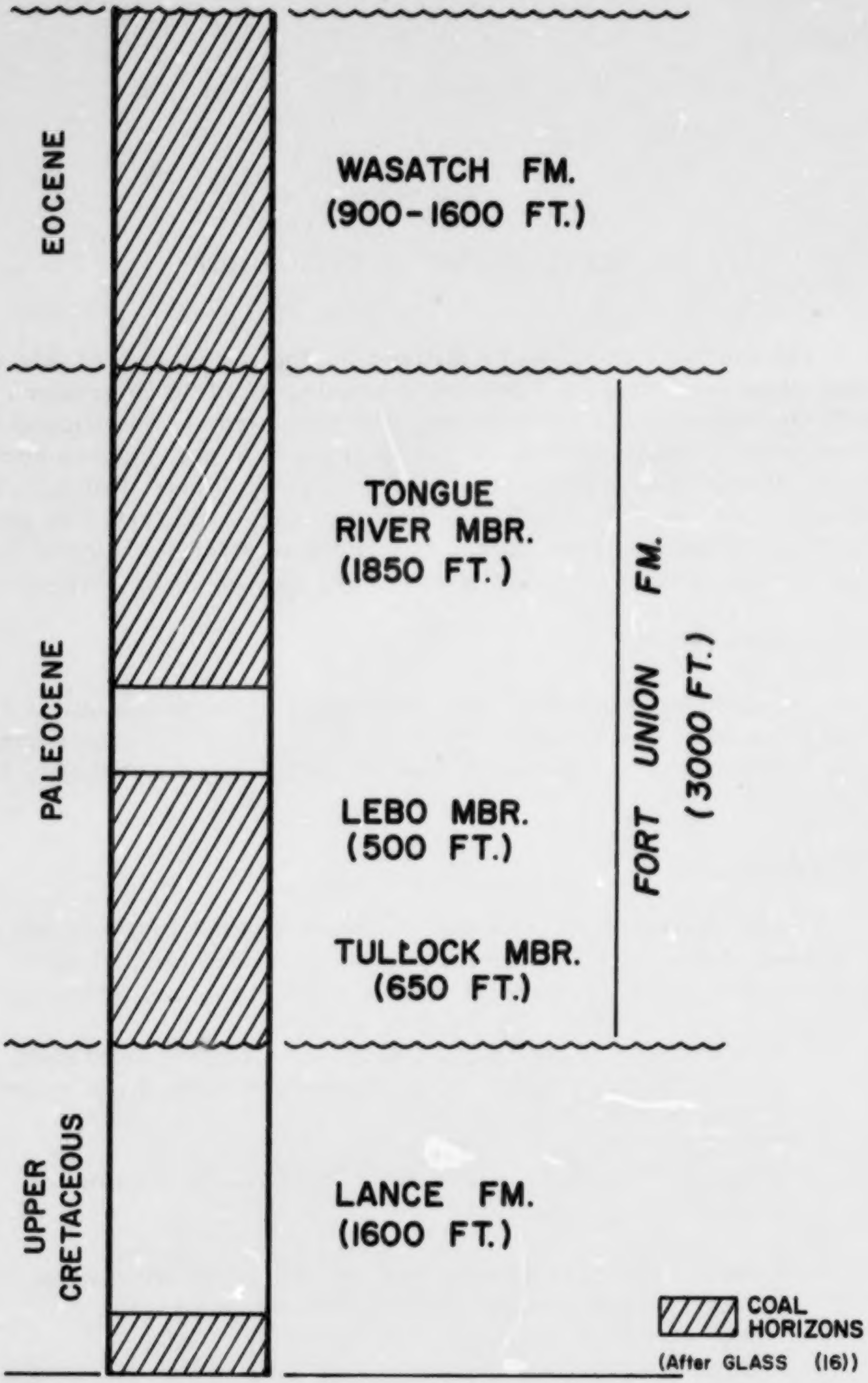

EOCENE
WASATCH FM.
(900-1600 FT.)
PALEOCENE
TONGUE RIVER MBR.
(1850 FT.)
LEBO MBR.
(500 FT.)
TULLOCK MBR.
(650 FT.)
FORT UNION FM.
(3000 FT.)
UPPER CRETACEOUS
LANCE FM.
(1600 FT.)
COAL HORIZONS
(After GLASS (16))

Figure 8. Coal-bearing formations in the Powder River region.

SECTION 6

METHODS OF INVESTIGATION

The methods which were utilized during the course of this investigation are discussed under the following headings: Field Operations and Laboratory Operations. As the investigation progressed, modifications of the techniques were made, and these are described in appropriate sections. These modifications were made primarily during Phase II of the study to conform to various field conditions and to changes suggested by preliminary conclusions drawn from the data. The recommended techniques for those wishing to utilize the predictive method are presented in Section 9.

FIELD OPERATIONS

The field work for this study consisted of the selection of drilling and sampling at selected sites. Each of these segments is described in subsequent sections. The field work was conducted from February, 1976, to August, 1977.

Site Selection

The selection of suitable and adequate sites throughout the semi-arid environment of the Rocky Mountain region proved to be difficult because strip mine sites were required to meet a majority of the following criteria:

- An existing coal strip mine must have been in operation at least 1 yr. (Lignite operations were beyond the scope of this study.)
- A mine of known or suspected ground-water movement through spoil materials.
- A mine of known or suggested ground-water movement through overburden and/or interburden material.
- A mine that was accessible for drilling equipment with a minimum of road building and disturbance to the environment.

- A mine that was in reasonable proximity to air transportation to allow for shipment of time-critical water samples.

- A mine that had visible ponded water in and/or adjacent to the mine operation.

- Permission from the mine owners and operators to conduct public research.

The first step in the process of site selection was to contact the owner and/or operator of a potential site. If tentative permission was granted for utilization of a site, an aerial reconnaissance by a geologist to gain rapid familiarity with a mine site was made. In particular, features such as the location of streams and ponds and their relationship to the mine operation, the presence of geologic faults and other structural features, the status of active and abandoned operations, and the existence of access roads for drilling were noted. Following the aerial inspection, a ground reconnaissance was undertaken to view the mine area at a closer perspective.

Having obtained aerial and ground reconnaissance data of those mines considered suitable for investigation, a literature search was conducted to determine the extent of any previous work and to develop a background knowledge of the hydrogeologic conditions. Mine operators and/or owners were again contacted, and a proposed drilling and sampling program was submitted for their approval and recommendations. Verbal permission for site access was solicited at this time pending written agreements. Preliminary hole locations were identified, and all permits for drilling were obtained before actual field operations were initiated.

Drilling

One drilling contractor was utilized for all drilling. The drilling was accomplished with a truck-mounted, combination, air-rotary drill rig. Holes were drilled with a $6\frac{3}{4}$-in. roller bit to the bottom of unconsolidated material and highly weathered rock, or to a depth of 20 ft, whichever was greater. Six-inch black steel pipe was then cemented through the unconsolidated section, and the drilling continued with a $5\frac{5}{8}$-in. roller bit to total depth.

Coring was accomplished with a 3-in. standard core barrel which employed a $5\frac{5}{8}$-in. OD face discharge diamond coring bit. Recovery of core throughout the course of the drilling program was in excess of 95%, although drilling was frequently slow--e.g., 15 min/ft.

In order to avoid contamination of any aquifers, no mud was used. All drilling was conducted with air or air-water mist. In rare instances, a lubricating soap was used. Records were kept of the water injection rate and subtracted from any well discharge (measured with a 2-in. Parshall flume and/or a container and stopwatch).

Each borehole producing water was cased to total depth with 5-in. PVC casing which was slotted at the water-producing zones. In the event that the water production remained essentially constant throughout the course of the drilling, only the bottom 10-ft section of the casing was slotted. Slots were made with a hand saw and staggered on opposite sides of the pipe approximately every 4 in. along the desired interval. Figure 9 shows a typical well completion.

Development of wells was accomplished by jetting the perforated zone with a tool designed to direct compressed air radially away from the drill stem and through the perforations. This procedure was continued until the water became substantially clear. All holes were completed with a cement surface seal poured into the casing annulus to a depth of approximately 5 ft. A locking steel cap was then set into place at the surface (see Figure 9).

In some cases, notably the alluvial aquifer of Foidel Creek at the Energy Fuels Mine, the clay content of the soil in which the well was drilled rendered the development of an open-cased well more time consuming and expensive than installing a lysimeter. Lysimeters were, therefore, installed in saturated soils where appropriate.

When used, each lysimeter was leached with 500 ml of 10% hydrochloric acid by introducing a vacuum to the lysimeter and allowing it to draw the acid through the cup. After leaching, the instrument was flushed with 1,000 ml of distilled water and installed in the well. Figure 10 illustrates the configuration and materials used for a lysimeter installation. All attempts were made to avoid contamination of the sample from rain or surface-water flow down the hole.

Samples obtained from surface and open-well sources required the collection of over 10 liters for analytical purposes. The sample volume obtained from lysimeters in the unsaturated zones in spoils or alluvial material did not exceed 150/ml; it was decided therefore that lysimeter samples would be collected only in saturated soil and only if the location of a particular sample was considered hydrogeologically critical.

The pressure-suction soil-water sampler was essentially discarded for sampling purposes during Phase II because the experience gained seemed

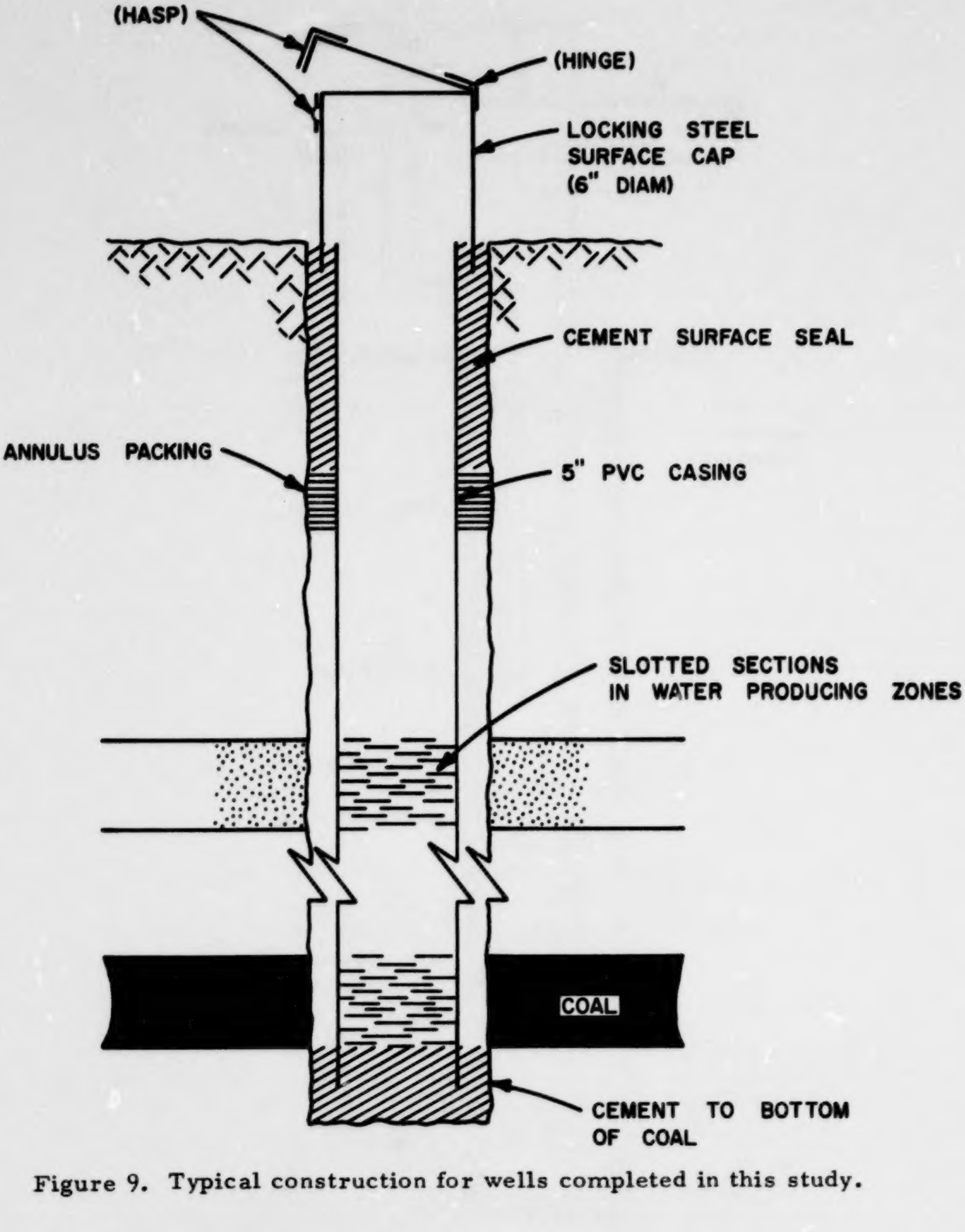

(HASP)
(HINGE)
LOCKING STEEL SURFACE CAP (6" DIAM)
CEMENT SURFACE SEAL
ANNULUS PACKING
5" PVC CASING
SLOTTED SECTIONS IN WATER PRODUCING ZONES
COAL
CEMENT TO BOTTOM OF COAL

Figure 9. Typical construction for wells completed in this study.

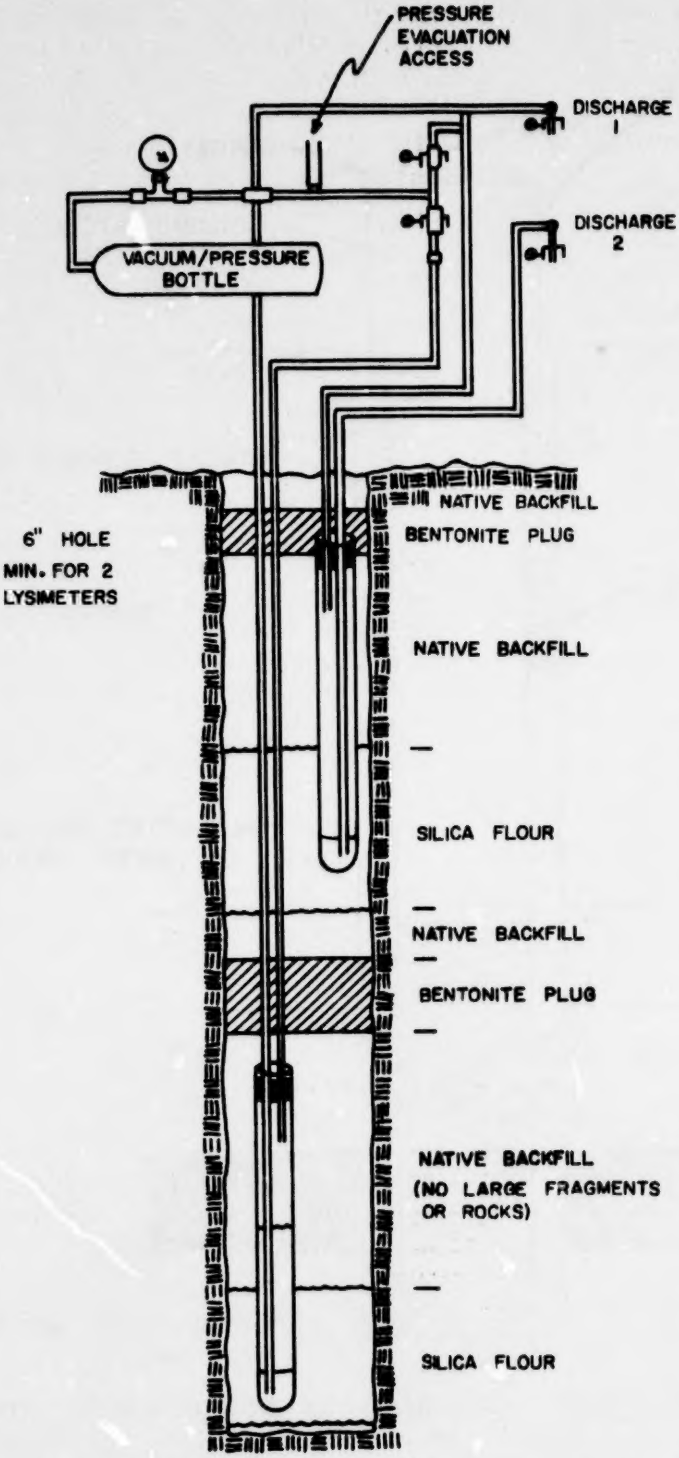

PRESSURE EVACUATION ACCESS
DISCHARGE 1
DISCHARGE 2
VACUUM/PRESSURE BOTTLE
NATIVE BACKFILL
BENTONITE PLUG
6" HOLE MIN. FOR 2 LYSIMETERS
NATIVE BACKFILL
SILICA FLOUR
NATIVE BACKFILL
BENTONITE PLUG
NATIVE BACKFILL (NO LARGE FRAGMENTS OR ROCKS)
SILICA FLOUR

Figure 10. Diagram of typical pressure-vacuum lysimeter installation.

to indicate potential problems with this method. In addition, research performed by Hansen and Harris (21) indicated that artificial concentration of ionic species was likely to occur with this method. Factors which contribute in varying degrees to the potential inaccuracies include soil porosity, degree of saturation of the sampled zone, size and thickness of porous cup, rate and duration of sampling, and the degree of initial vacuum applied to the sampler as well as whether a constant or falling rate vacuum was applied.

Sampling Techniques

Sampling at each site consisted of collecting water and rock samples. Water samples were collected from outside of the influence of mine operations, within the mine area, and downstream from the mine area.

When drilled with a tricone bit, the overburden was sampled at 5-ft intervals. The cuttings were logged, bagged, and numbered sequentially for shipment. Overburden core was treated similarly. When a run was completed, the core was marked by parallel red and green lines running the length of the core. Footage was marked directly on the core. In rare instances of core loss, the loss was assumed to be at the run unless lack of continuity could be verified. The core was then logged for lithology, boxed, and prepared for shipment. No attempt was made to retain the moisture content of the core.

Highwall-faces and road cuts were also used for the collection of some stratigraphic information. Samples were collected from exposures of representative rock units and/or zones of important lithologic or mineralogic change.

Water samples were obtained from both surface waters and wells. Surface waters sampled included ponds, springs, streams, and flumes. Ground-water samples were obtained from wells or from lysimeters. The samples obtained using lysimeters were invariably small, and a complete analysis of waters collected in this manner was not possible. Water samples collected were divided into as many as six containers, depending on the method of preservation, and the amount of sample available. Some of each sample was filtered using a Plexiglas pressure filter pressurized with nitrogen. The first filtration was accomplished with a No. 24 glass fiber paper followed by a second filtration with a 0.45 μm millipore filter.

Sample Preparation --

Container 1 was used for immediate field measurements and not treated in any way. After obtaining a sample, measurements were made of temperature, conductivity, pH, and in some cases, Eh. Commercial test kits were used to determine dissolved oxygen, carbon dioxide, and hydrogen sulfide. In later phases of the study, test kits were also used to determine alkalinity, chlorine, sulfate, and hardness as a means of screening water samples for complete laboratory analysis. The analytical methods used for these field tests are listed in Table 1.

Container 2 was a 1-pt filtered sample preserved by adjusting to pH 4.0 using a pH meter with phosphoric acid and adding 0.5 g copper sulfate. It was shipped in a glass container and the phenol content measured within 24 hr. This test was not performed on the lysimeter samples.

Container 3 was a 1-pt filtered sample shipped in a glass container, wrapped to exclude light and kept in ice. Tannin plus lignin were determined with 7 days. This test was not performed on the lysimeter samples.

Container 4 was an unfiltered sample, shipped in either glass or plastic, wrapped to exclude light, and kept in ice. Initially, a 1-gal sample was collected; later, 1 qt was considered adequate and, for the lysimeter samples, 120 ml sufficed if coupled with analytical methodology changes. The major anions were determined in this sample within 24 hr and the total dissolved solids and halogens within 7 days.

Container 5 was a 1-gal filtered sample shipped in a plastic container and preserved by adjusting to pH 2.0 using a pH meter with nitric acid. The major cations, trace metals, and radiation level were determined on this sample within 6 mo. For the lysimeter samples, only 50 ml was allocated to these determinations necessitating the omission of those tests requiring a large amount of sample.

Container 6 was a 1-qt filtered sample, shipped in either glass or plastic and preserved by adjusting to pH 2.0 using a pH meter with sulfuric acid. Kjeldahl-nitrogen, nitrite plus nitrate, and total organic carbon were determined on this sample within 24 hr. These determinations were not performed on the lysimeter samples.

LABORATORY OPERATIONS

Laboratory operations consisted basically of two major tasks: One, to define the lithology and mineralogy of the solid samples, and two, to analyze the water samples in considerable detail.

Mineralogical Methods

The mineralogic analysis of a typical sample constituted three levels of detail. The first step was a hand-specimen examination of most of the core, aided by binocular microscopic examination and simple chemical

TABLE 1. FIELD ANALYTICAL METHODS

Determination	Method
Alkalinity	Drop titration, sulfuric acid
Carbon dioxide	Drop titration, sodium hydroxide
Chloride	Drop titration, silver nitrate
Conductivity	Conductivity meter
Dissolved oxygen	Drop titration, phenylarsine oxide
Eh	pH meter, platinum-calomel electrodes
Hardness	Drop titration, ethylenediaminetetraacetic acid
Hydrogen sulfide	Stain, lead salt impregnated paper
pH	pH meter, glass-calomel electrodes
Sulfate	Turbidometric, barium chloride
Temperature	Thermometer

tests to identify specific minerals. This enabled a determination of the rock type and the identification of any unusual quantity of accessory minerals.

The second step was to grind a split of the rock sample for a determination of the minerals present by x-ray diffraction and a determination of the semiquantitative elemental composition by x-ray fluorescence. A limited number of thin and polished sections were prepared in order to identify microscopically those minerals that might be present in only trace amounts and, therefore, would not be detected in an x-ray diffractometer scan.

The third step, and the most detailed method of analysis, involved the separation of certain mineral constituents from the rock and examining these by various methods. The mineral groups studied at this level of detail were primarily the clay minerals and, secondarily, the heavy minerals which included the sulfides. The clay minerals were extracted by settling in water and the heavy minerals were extracted by separation using a 2.85 sp gr fluid.

Sample Preparation --

In all cases no more than one-half of each core, cutting, or spoil sample was processed. The other half was retained. Where possible, 200 to 300 g of sample was processed. The sample was stage ground to minus 65 mesh using either a hand mortar and pestle or a Buehler pulverizer. A 60-g portion of this sample was split out and ground to minus 200 mesh for bulk x-ray diffraction and chemical analysis. Other portions of the minus 65 mesh sample were used for clay separations.

A minus 2 μm or clay-size fraction was obtained by disaggregating 10 g of the sample and allowing the sample to settle in a 1-liter cylinder using a dispersing agent for 24 hr, then decanting. Several portions of this clay-size fraction were collected on millipore filters for subsequent examination. In some cases, a known volume of this fraction was removed by pipette, evaporated to dryness, weighed, and the weight percent of the minus 2 μm fraction calculated.

Mineral Identification --

The primary objective of the initial hand-specimen examination of the overburden core samples was to determine the lithology. This examination involved the determination of grain size, color, amount of included organic matter, and any visible structural features. In addition, the presence of specific minerals was noted, either visually or by simple tests. Specifically, the minerals present and the tests used for them were:

- Clay - slippery when wet
- Calcite - effervescence in dilute HCl
- Gypsum - yellow stain with mercuric nitrate
- Pyrite - metallic luster, yellow color
- Limonite - yellow-brown stain
- Siderite - brown, with carbonate cleavage

X-ray diffraction is the most important method for the identification of crystalline substances. It must be stressed that x-ray diffraction patterns are characteristic of the crystal form and of the chemical compound present rather than of the elements or chemical groups making up this compound.

The data were obtained by the spectrometric powder technique using a diffractometer equipped with state-of-the-art electronics, a crystal monochromator (to reduce scattered and fluorescent background radiation), an axis controller (to drive and to precisely position the goniometer), and a telecomputer interface to control the data acquisition of the entire system.

Bulk rock samples were examined by packing them into standard aluminum holders, whereas clays were examined by collecting them on a millipore filter and supporting the filter on a glass slide. X-ray determination of clay species is based on the fact that some clays expand when they absorb some organic compounds within their structure. In this project, the clays were treated with ethylene glycol whereupon vermiculite, if present, expanded from 12 to 14Å and montmorillonite expanded from 14 to 17Å. When both clays are present, however, interpretation becomes uncertain.

A limited number of thin sections were cut and examined by transmitted light-microscopy in the early phases of this study. However, because of the limited amount of pertinent information revealed, this type of examination was later discontinued.

Some polished sections were also prepared and examined using reflected light-microscopy, primarily to identify and to determine the presence and mode of occurrence of pyrite. The scarcity of pyrite led to the discontinuance of this method of investigation.

Chemical Constituents --

Three methods of obtaining chemical data were used. First, the major and minor constituents of the bulk rocks were determined by wet chemical analyses. This type of analysis gives information on the amount of light element constituents and on the state of oxidation of the iron. A second method of obtaining chemical data, and one used consistently throughout the program, involved x-ray fluorescence analysis of dry powdered samples. This technique gives semiquantitative information on the heavy metal content of the samples. Both bulk rocks and clays collected on millipore filters were examined in this manner.

A third method of obtaining chemical data, employed in some cases, was the determination of the amount of exchangeable cations held by the clay size fraction. This method is referred to as the cation exchange capacity (CEC). Cation exchange capacities were determined because of the presence of montmorillonite and/or vermiculite in most of the samples and because of the high heavy metal content of the clay size fraction.

Most of the procedures used for CEC determination have been developed by soil scientists and involve the use of a 50- to 100-g sample. For this program, it was established that the required sensitivity could be obtained only if the CEC was determined on the clay-size fraction rather than on the bulk sample. Consequently, a semimicro procedure was developed requiring only 100 to 200 mg of sample and use of an ammonium-specific ion electrode.

Water Analysis

The methods used for the laboratory analyses of the water samples are listed in Table 2. Those marked with an asterisk are described in Standard Methods for the Examination of Water and Wastewater, 13th edition, published jointly by AWWA, APHA and WPCF, 1971.

The main changes in methodology made during this program were directed toward achieving either increased precision or economy of sample.

Major changes included:

Carbon Dioxide. Initially, the carbon dioxide content was determined from a nomograph which incorporated field determinations of temperature, pH, and laboratory determinations of alkalinity and total dissolved solids. Because of the high total dissolved solids encountered, and the inherent inaccuracies of the method, a field titrimetric method was substituted.

Sulfate. Initially, the turbidimetric method was used. Because most of the samples were high in sulfate, the gravimetric method was later substituted. When only small sample volumes were available, such as from lysimeters, the turbidimetric method was used.

Silica. Initially, silica was determined gravimetrically. Because the silica content of most samples was generally low, higher precision and

TABLE 2. LABORATORY ANALYTICAL METHODS

Determination	Method	AWWA Method
Aluminum	Colorimetric, alizarin red-S	
Arsenic	Atomic absorption, hydride generator	
Barium	Atomic absorption	*
Bicarbonate	Titration, hydrochloric acid	*
Boron	Colorimetric, carminic acid	*
Bromide	Colorimetric	
Cadmium	Atomic absorption	*
Calcium	Atomic absorption	
Carbon, total organic	Coulometric after combustion	
Carbonate	Titration, hydrochloric acid	*
Chloride	Titration, silver nitrate/potassium chromate	*
Chromium	Atomic absorption	*
Copper	Atomic absorption	*
Fluoride	pH meter, specific ion electrode	
Iron	Atomic absorption	*
Lead	Atomic absorption, carbon rod	
Lithium	Atomic absorption	
Magnesium	Atomic absorption	*
Manganese	Atomic absorption	*
Mercury	Atomic absorption, vapor flameless	
Molybdenum	Colorimetric, potassium thiocyanate	
Nickel	Atomic absorption	
Nitrate (+nitrate)	Colorimetric, phenoldisulfonic acid	*
Nitrogen (total)	Kjeldahl, titration, sulfuric acid	*
Phenols	Colorimetric, 4 aminoantipyrine	*
Phosphate	Colorimetric, molybdivanadate	*
Potassium	Atomic absorption	
Radiation ($\alpha + \beta$)	Instrumental	
Selenium	Atomic absorption, hydride generator	
Silica	Colorimetric, reduced molybdosilicic acid	*
Sodium	Atomic absorption	
Strontium	Atomic absorption	
Sulfate	Gravimetric, barium nitrate	*
Tannin and lignin	Colorimetric, tungsto- and molybdophosphoric	
Titanium	Colorimetric, disodium 1-2 dihydroxy benzene 3-5 disulfonate	
Total Dissolved Solids	Gravimetric	*
Zinc	Atomic absorption	*

* Described in Standard Methods for the Examination of Water and Wastewater, 13th edition, published jointly by AWWA, APHA, and WPCF, 1971.

greater economy of sample was obtained by using the colorimetric heteropoly blue method.

Titanium. The colorimetric peroxide method originally used was later changed to a considerably more sensitive colorimetric method based on the use of disodium 1,2,dihydroxybenzene3,5,disulfonate.

Trace Metals. Initially, many of the trace metals were determined using carbon rod atomic adsorption. Because of the tedious and time consuming nature of the method, most of these metals were later determined by standard atomic absorption after concentration by evaporation.

Quality Control --

The reasonability and reproducibility of field and laboratory techniques were estimated in three ways: duplication, summation checks, and by equilibrium considerations.

Duplication. The most straightforward method of checking analyses is sample duplication. Two samples taken from a locality at the same time showed excellent analytical reproducibility as shown in Table 3.

Duplication of samples from the same location taken days or weeks apart showed marked differences in field determinations of temperature and pH. The reproducibility of most of the ions, such as sulfate, calcium, and magnesium, generally fell with 20%.

Summation Checks. In all cases, data were screened using the following tests before further calculations were carried out. In some cases, minor adjustments were made in calculation methods depending on the relative confidence levels in measurements of dissolved oxygen, temperature, pH, and Eh.

Analytical method checks included the calculation of cation-anion charge balance (error not to exceed 30%), the percentage error in measured vs calculated values of total dissolved solids (error not to exceed 20%), the ratio of the measured total dissolved solids to the conductivity (should lie between 0.55 and 0.77), and a check on the oxidation potential calculated from pH (Eh must exceed 0.059 pH--this represents the lower stability limit of water).

Equilibrium Considerations. In the absence of carbonate, bicarbonate was required to be less than 10 meq/liter. When the pH of the solution was greater than 9.0 and carbonate was present, carbon dioxide was required to be zero and the sum of calcium plus magnesium was required to be less than 2 meq/liter. These constraints reflect what is considered to be a

TABLE 3. REPRODUCIBILITY OF ANALYSES KEMMERER MINE, WYOMING

	Sample 1	Sample 2
Temperature °C	13.0	13.0
pH	8.1	8.1
	mg/l	mg/l
HCO_3^-	146.7	143.1
$SO_4^{=}$	2,025.0	2,025.0
F^-	0.2	0.2
Cl^-	18.5	20.0
Br^-	<0.1	<0.1
$(NO_2 + NO_3)$ as NO_3	5.9	0.09
PO_4	0.98	0.09
Ca^{++}	382.0	382.0
Mg^{++}	344.0	344.0
Sr^{++}	5.55	5.55
Na^+	44.8	45.4
K^+	20.1	20.1
Li^+	0.223	0.225
SiO_2	0.7	1.42
Fe	0.77	0.15
Al	0.27	0.23
B	0.4	0.9

reasonable error for the methods of analysis used and what are the known geochemical limitations for equilibrium distribution of ions and ion complexes in aqueous solutions. If these conditions were not met, the analysis was not considered in the interpretive phase of this study.

SECTION 7

MINE SITES INVESTIGATED

This section of the report describes the eight mine sites investigated. A detailed description of the sites, types of data collected, discussion of results, and relationships that led to the development of the predictive methods, are discussed separately for each mine. The sites were selected on the basis of the criteria discussed in Section 6.

ENERGY FUELS MINE

The Energy Fuels Mine is located in Routt County, Colorado, between the towns of Craig and Steamboat Springs. The mine is owned and operated by the Energy Fuels Corp. The Energy Fuels Mine was the first of the mines investigated to determine if a correlation exists between mineralogy and quality of ground water associated with coal-strip-mine operations.

Topography in the mine area consists primarily of rolling, somewhat elongated hills with some cliff formation as a result of resistant sandstone outcroppings. The main drainage from the mine area is via Foidel Creek which occurs to the northwest of the mine operation, and flows to the northeast. Figure 11 shows the drainage pattern for both the Energy Fuels Mine and the Edna Mine (the latter is the second mine to be discussed).

Climate

A weather station is currently maintained at the Energy Fuels Mine; however, the data collected to date were insufficient to utilize in this investigation.

The mean annual temperature at Steamboat Springs, approximately 9 mi east, is 39°F, and the mean annual precipitation is 24.0 in. The precipitation is probably higher than what can be expected at the mine site because of the higher elevations at Steamboat Springs. Annual precipitation between 15 and 22 in./yr would likely be more representative of the mine site. The town of Hayden has an average annual precipitation of 16.2 in./yr, and reportedly is fairly evenly distributed throughout the year (22). Precipitation in this area is predominately in the form of snow, with summer showers

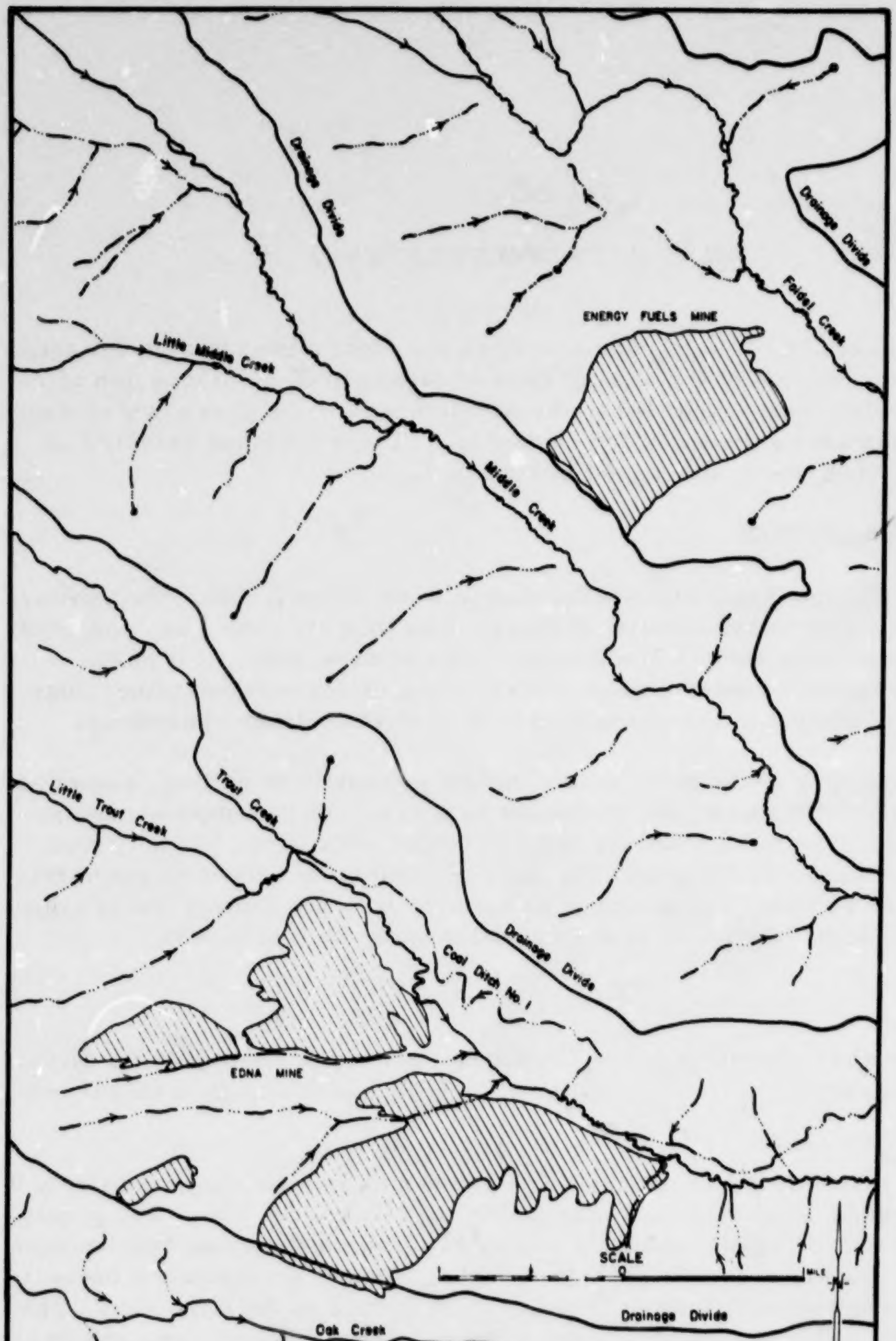

Drainage Divide
Drainage Divide
Foidel Creek
ENERGY FUELS MINE
Little Middle Creek
Middle Creek
Little Trout Creek
Trout Creek
Coal Ditch No. 1
Drainage Divide
EDNA MINE
SCALE
0
MILE
Drainage Divide
Oak Creek

Figure 11. Surface drainage in the vicinity of the Energy Fuels and Edna Mines, Colorado.

accounting for the remainder. The average annual evaporation rate exceeds the average annual precipitation rate at the Energy Fuels Mine.

Geology

The Energy Fuels Mine lies within the Twentymile Park Syncline in the southeastern part of the Yampa Field. Rocks exposed in the area are of Late Cretaceous Age and include thick sequences of shale, sandstone, and coal (22). These units comprise the Mesaverde Group which conformably overlies the Mancos shale.

The rocks of primary concern are those of the Williams Fork Formation. This formation ranges from 1,100 to 2,000 ft in thickness, and contains three principal units: a lower unit that contains the coal being mined at the Energy Fuels Mine, a middle unit that consists of the Twentymile Sandstone Member, and an upper unit which consists of sandstone and shale. The lower coal-bearing unit of the Williams Fork contains the Lennox and Wadge seams of the middle coal group as defined by Fenneman and Gale (23). These coals occur between the Trout Creek and Twentymile Sandstones. At the Energy Fuels Mine, only the Wadge seam, most uniformly of good quality and thickness, is being mined. The Lennox seam has been eroded. The Wadge seam is fairly consistently between 8- to 10-ft thick. It is of bituminous rank, and has been described as "hard and shiny" (22). Approximately 60 to 80 ft of overburden overlies this coal in the vicinity of the Energy Fuels Mine. Figure 12 presents a detailed stratigraphic column of Hole CD-7A showing the basic geologic section found in the area of the Energy Fuels Mine. Figure 13 shows the legend for detailed core description diagrams.

Faulting in the Energy Fuels Mine area is evident in the cliff-forming Twentymile Sandstone outcrop which overlooks the mine area from the north. All of the faults observable are normal, with displacements ranging from a few feet to approximately 150 ft. These faults trend northwest-southeast throughout the area. Figure 14 shows an idealized block diagram for a portion of the Energy Fuels Mine.

Sampling Points

Because the Energy Fuels Mine was the first to be investigated, a rather extensive sampling program was conducted. Although initial plans called for sampling upgradient, within, and downgradient of the mine spoils, in terms of ground-water movement, some modification to this plan was necessitated by accessibility (see Figure 15). Seven holes were drilled in the spoil area and seven outside the spoil area. The field logs for all holes are presented in Appendix A.

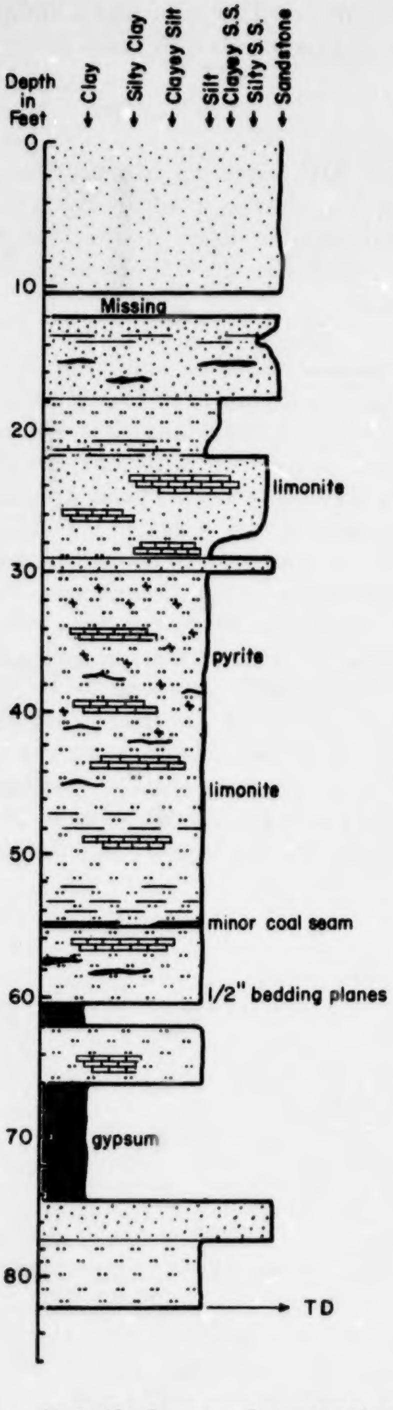

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
30
40
50
60
70
80
Missing
limonite
pyrite
limonite
minor coal seam
1/2" bedding planes
gypsum
TD

Figure 12. Detailed core description from Hole CD-7A. Energy Fuels Mine, Colorado.

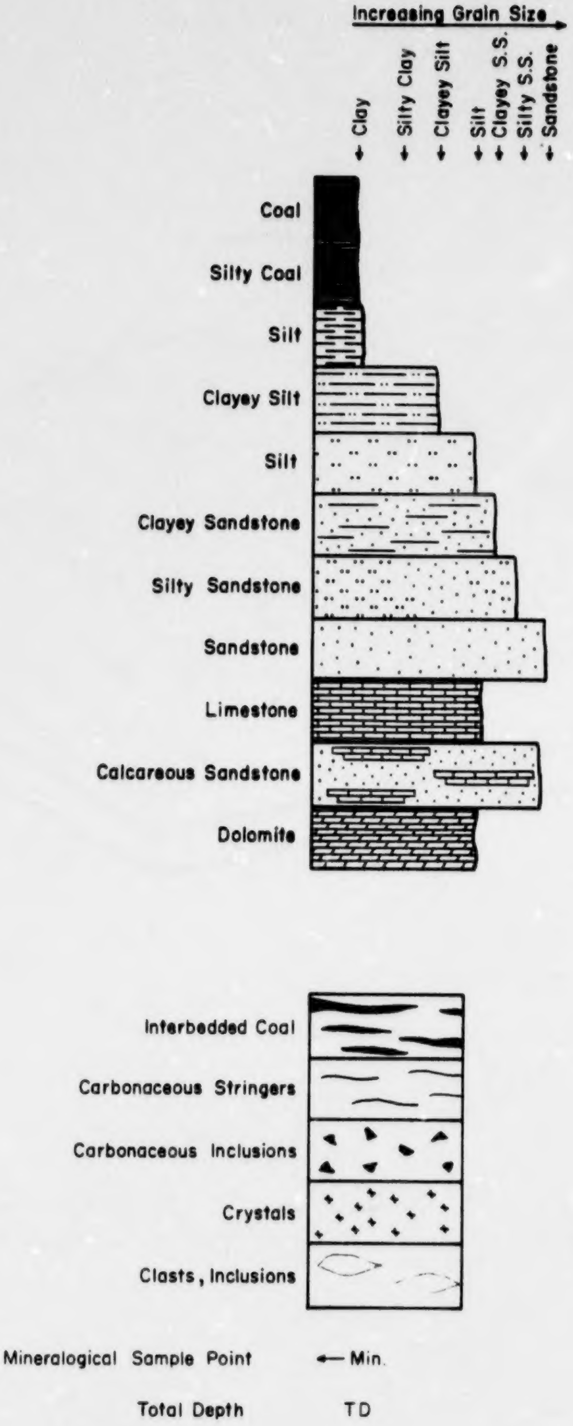

Increasing Grain Size
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
Coal
Silty Coal
Silt
Clayey Silt
Silt
Clayey Sandstone
Silty Sandstone
Sandstone
Limestone
Calcareous Sandstone
Dolomite
Interbedded Coal
Carbonaceous Stringers
Carbonaceous Inclusions
Crystals
Clasts, Inclusions
Mineralogical Sample Point
← Min.
Total Depth
TD

Figure 13. Legend for detailed core description diagrams.

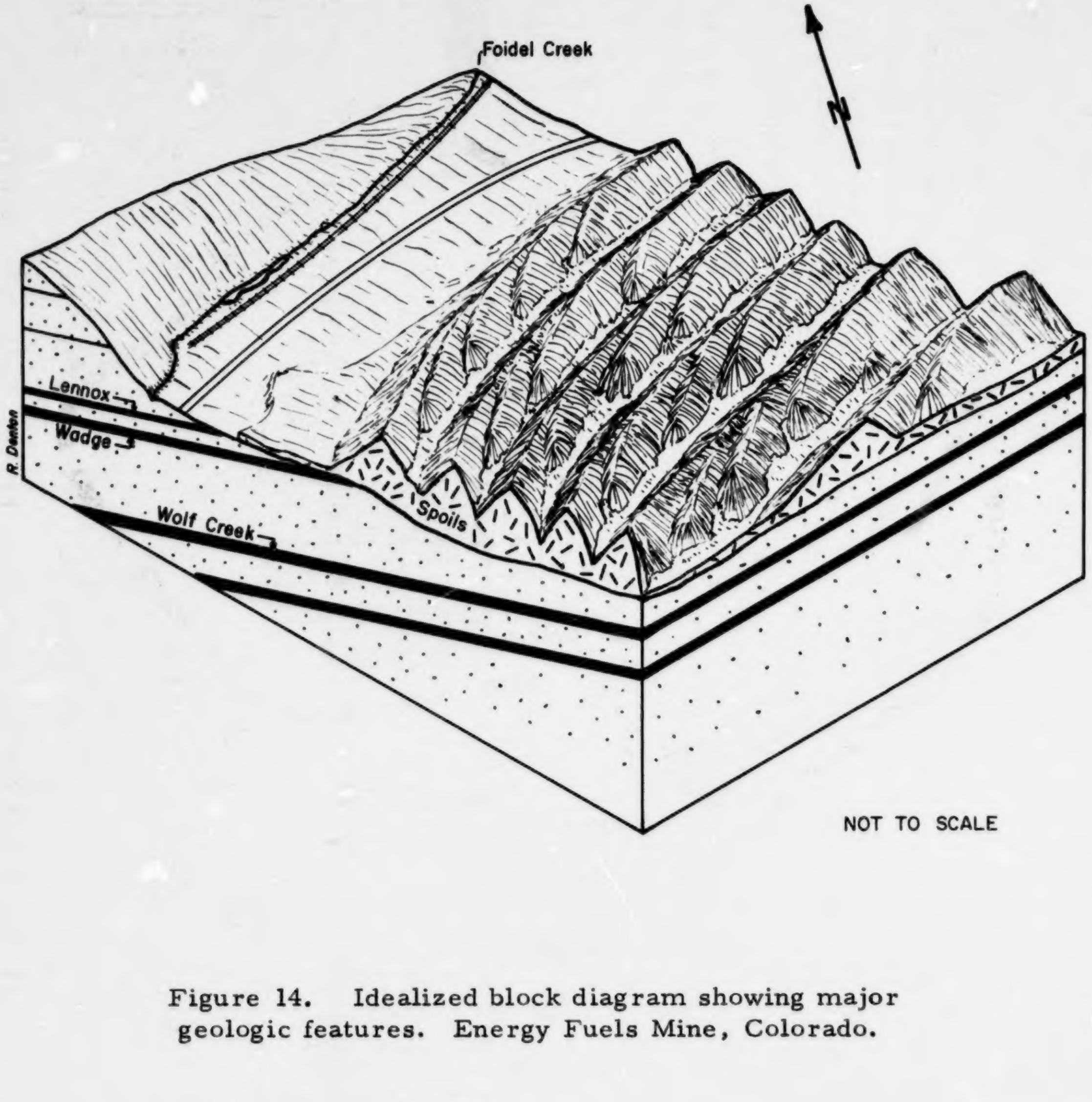

Foidel Creek
N
Lennox
Wadge
Wolf Creek
Spoils
R. Denton
NOT TO SCALE

Figure 14. Idealized block diagram showing major geologic features. Energy Fuels Mine, Colorado.

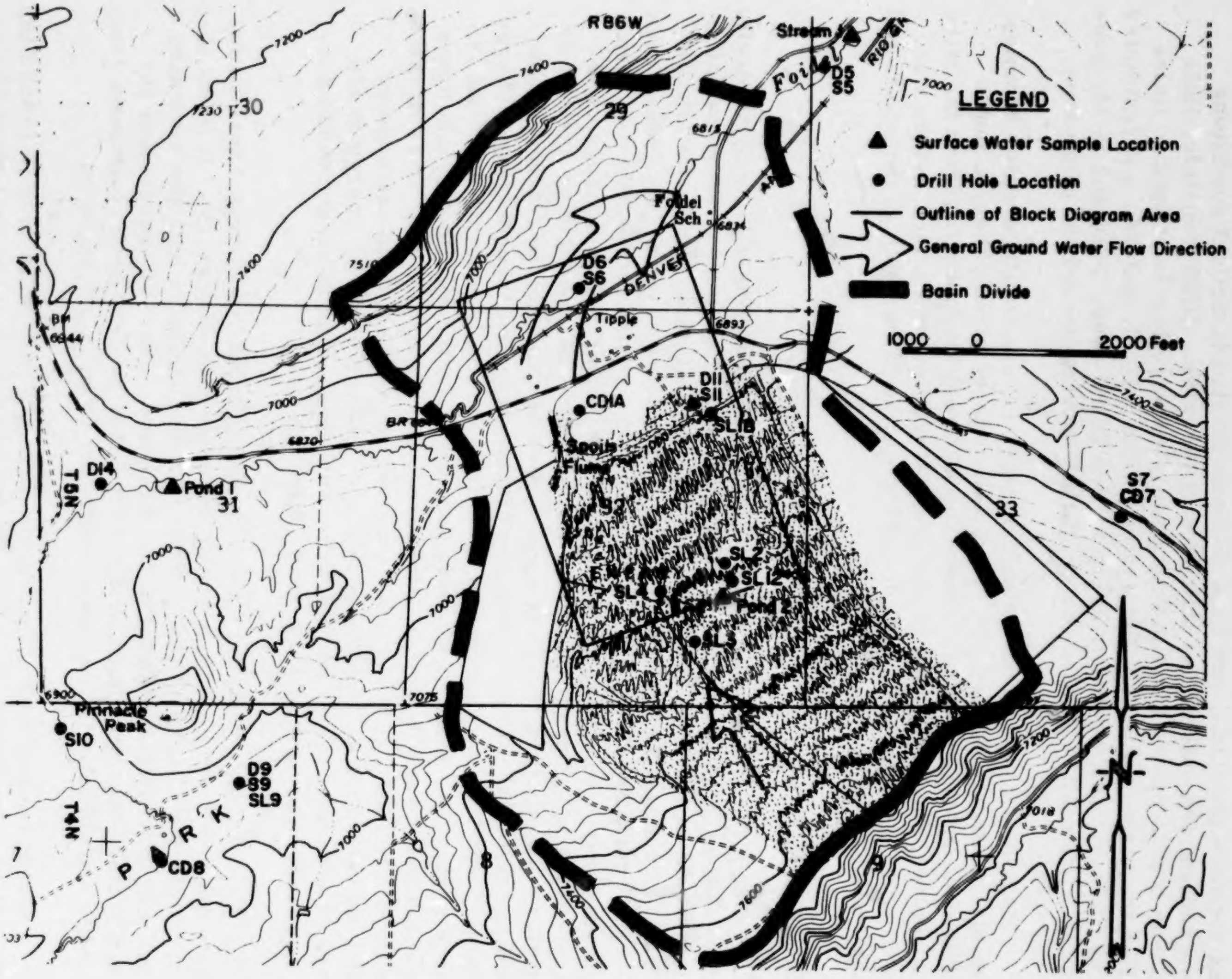

LEGEND
▲ Surface Water Sample Location
● Drill Hole Location
Outline of Block Diagram Area
General Ground Water Flow Direction
Basin Divide
1000 0 2000 Feet
R86W
T5N
T4N
Stream
D5
S5
D6
S6
Tipple
Foidel Sch
DENVER
CD1A
D11
S11
SL1B
Spoils Flume
SL2
SL12
SL4
Pond 2
SL3
S7
CD7
D14
Pond 1
Pinnacle Peak
S10
D9
S9
SL9
CD8
P R K
29
30
31
32
33
8
9
7000
7200
7400
7600
6820
6893

Figure 15. Sample location map. Energy Fuels Mine, Colorado.

Holes CD-8 and D-9 were located to represent conditions upgradient and outside the influence of the mine, Hole D-6 was located to reflect conditions opposite the mine, and Hole D-5 was located to reflect conditions downgradient and outside the influence of the mine. (Unfortunately, Hole D-5 was lost to caving and the water samples were lost in transit.) Holes drilled to obtain data within the spoils include: D-11, CD-1A, and lysimeter Holes SL-2, 3, and 4. Other holes drilled in the area, D-10 and D-14, provided data on shallow ground-water quality moving toward the mine area.

In addition to ground-water samples, several surface water samples were also collected. These included waters from three ponds, a flume draining the spoils, and water from Foidel Creek downstream from the mine (see Figure 15). Knowledge of the chemistry of these surface waters was important to the interpretation of shallow ground water both in the spoils and in the undisturbed overburden.

Hydrogeology

Recharge to the rock units within the Energy Fuels Mine area results from direct infiltration of precipitation and snowmelt, and to some extent from stream inflow. Several streams, Foidel, Middle, and Little Middle Creeks, flow northeastward across the strata lying between the Trout Creek and Twentymile Sandstones and originate to the southwest of the mine area. Although these streams are intermittent, they could act as sources of recharge to the adjacent alluvium and underlying rock units during periods of high flow. In addition, these streams cross several northwest-southwest trending faults which may be capable of receiving and transmitting recharge to deeper aquifers. Ponds within the mine area could also act as small recharge basins, but the high evaporation rates and the silting of the bottoms would not make them a significant source of recharge. Tributaries of the Middle Creek System, which may receive some runoff from the Mancos Shale, do not enter the overburden or spoil material at the Energy Fuels Mine. These waters pass 600 ft below the area of the mine and would provide recharge only to the rock units below the coal.

Foidel Creek forms the main drainage from the Energy Fuels Mine, and its quality could be influenced by the mine (see Figure 15). It flows almost totally over rocks of the Williams Fork Formation with the exception of one small stretch southwest of the mine area where it passes over the Lewis Shale. Any contribution of sulfates into Foidel Creek, upstream from the mine, would most likely have originated from this formation.

Ground-water movement in the Energy Fuels Mine area is toward the northeast or toward the axis of the Twentymile Park syncline. Most likely, this movement continues along the axis of the syncline and discharges into the Yampa River. Ground-water movement from the spoils area would be in essentially the same direction with perhaps some movement to the north toward the alluvium of Foidel Creek (see Figure 15).

Transmissivity values, or the rate at which water can move through a unit width of material under a unit hydraulic gradient, ranged from 0.82 ft^2/day to 4.6 ft^2/day for the deeper rock units in the mine area. Similar tests on alluvial materials (conducted by the U. S. Geological Survey) produced transmissivities as high as 9.7 ft^2/day. The sampled spoil pile materials generally did not contain sufficient water to warrant the calculations of transmissivity values.

Some ground water discharges from the mine area as springs and seeps immediately above Foidel Creek, and some flows underground into the alluvium, and then into Foidel Creek. Springs or seeps were noted at the bottom of the spoil cut; however, very little water was encountered in the spoil-pile drill holes. Essentially, only two water-bearing units were encountered during the drilling at the Energy Fuels Mine: the alluvial materials, and the sandstones associated with the coal. The sandstone-coal unit is treated as one unit in this discussion because the water-production zones of the sandstones were not readily distinguishable from those that appeared in the coals. Yields as high as 800 gpm have been reported from the Mesaverde Group, and as high as 980 gpm from the valley-fill materials in northwestern Colorado (24). No such volumes were encountered in the holes drilled at the Energy Fuels Mine.

Mineralogy

A lithologic examination of the core from Hole 7-A drilled through the overburden showed the major rock types to be siltstone, 56%, sandstone, 35%, and coal, 12%. The stratigraphic column is shown in Figure 12. Most of the rocks examined are, to some extent, calcareous. Small quantities of both pyrite and gypsum were observed throughout the core.

X-ray diffraction scans (see Table 4) show that dolomite generally predominates over calcite and that small amounts of siderite are ubiquitous. A limited number of samples were analyzed for their major and minor constituents by wet chemical analysis (Appendix Table B-1). The most obvious feature shown by these analyses is the wide variation in silica, iron, carbonate, and water content of these rocks. The sulfate and sulfide content, when detected, was small. Titanium content, on the other hand, is relatively high and roughly proportional to the aluminum content. X-ray diffractometer scans of the clay size fraction of the samples revealed that in most cases kaolinite was the major clay mineral present, generally associated with minor amounts of clay size quartz and clay-mica. Also minor amounts of vermiculite and/or montmorillonite are present. Although the cation exchange capacities of the clay size fractions are moderate, the clays make

TABLE 4. X-RAY DIFFRACTION DATA ENERGY FUELS MINE, COLORADO

	1-B		SL-4	D-5				D-6		SL-3		
	0-5'	30-40'	0-10'	0-5'	95-100'	200-205'	300-305'	0-5'	95'	0-5'	25-30'	45-50
Quartz	60	55-60	65-70	60-65	50-55	50	50	50	50	65	65-70	65-70
Feldspars	15-20	20-25	5-10	20	20	20	10-15	15	15	10	10	10
Kaolinite	10	5-10	5-10	10	5	5-10	10-15	10-15	20	10	5-10	5-10
Montmorillonite	--	5-10	--	10	15	15	10-15	15	--	--	--	--
Mica	5-10	5-10	5	--	5	5-10	5-10	5	5	5	--	--
Dolomite	5-10	3	10	--	5	3-5	5	--	--	5	3	3
Calcite	5	Tr	5	3	3	3-5	5	7-10	3	5	3	3
Siderite	Tr	--	3	Tr	--	--	--	--	--	--	--	--
Gypsum	--	--	--	--	--	--	--	--	--	--	--	--
Pyrite	3	--	--	--	5-10	5	5	--	5	--	--	--
Magnetite	--	--	--	--	--	--	--	--	--	--	--	--
CLAY FRACTION (<2μ)												
Wt % of Total	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.19	0.14	0.16
Kaolinite	P	M	P	m	m	m	m	m	M	M	M	M
Illite	m	Tr	m	Tr	m	m	m	m-Tr	m	m	m	m-Tr
Montmorillonite	--	--	Tr	m-M	m-M	m-M	m	m-Tr	Tr	m-Tr	m	m
Vermiculite	m-Tr	--	Tr	Tr	Tr	Tr	Tr	Tr	Tr	m-Tr	--	m

TABLE 4. X-RAY DIFFRACTION DATA (Cont.)
ENERGY FUELS MINE, COLORADO

	D-9					Heavy Sep.	CD-7A												
	0-5'	45-50'	95-100'	145-150'	171-175'	95-100'	13'	18'	21'	28'	29'	36'	42'	50'	53'	58'	64'	77'	82'
Quartz	65	55	45-50	55-60	70-75	15-20	60-70	65	70	70	65-70	70-75	70	65-70	65	60	70-75	70-75	65-70
Feldspars	10-15	10	5	10	5	--	10-15	10	10	10	10-15	10	10	10-15	5-10	5-7	15-20	15-20	10-15
Kaolinite	5-10	15	20	10	10	--	10-15	10	5-10	5-10	5-10	10	10	5-10	10-15	10	10	5-10	5-10
Montmorillonite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Mica	5-10	5	--	10	--	15	5-10	--	--	--	--	--	--	--	5	5	--	5	5
Dolomite	--	5-10	5	5	5	--	-	10-15	5-10	5-10	5-10	5	5-10	5-10	5-7	5	--	--	5
Calcite	5	5-10	--	Tr	Tr	--	--	5	5	5	5	--	5	5-10	3-5	3-5	--	--	--
Siderite	--	5	5	Tr	--	30-40	Tr	--	--	--	--	--	3	Tr	--	10	5	--	5-10
Gypsum	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pyrite	--	--	5	5	--	20-25	--	--	--	--	--	--	--	--	5	--	--	--	--
Magnetite	--	--	--	Tr	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CLAY FRACTION (<2μ)																			
Wt % of Total	ND	ND	ND	ND	ND	ND	0.21	ND	ND	ND	ND	ND	ND	ND	ND	0.33	ND	ND	ND
Kaolinite	m-M	m-M	M	M	M	--	M	M	M	M	M	M	M	M	M	M	M	M	M
Illite	m-M	m	m	m	m	--	m	m	m	m	m	m	m	m	M	M	M	M	M
Montmorillonite	Tr	--	Tr	Tr	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vermiculite	Tr	m-Tr	m-Tr	m-Tr	m-Tr	--	m	m	Tr	Tr	Tr	m	Tr	Tr	m	m-Tr	m-Tr	Tr	m-Tr

ND -- not determined   P -- predominant (est. +80%)   M -- major (est. 40-80%)   m -- minor (est. 10-40%)   Tr -- trace (est. 1-10%)

up only a small proportion of the total sample.

The x-ray fluorescence analyses of the bulk rocks reveal no obvious anomalies. For the clay-size fraction, these analyses show significant enrichment in copper, zinc, chromium, nickel, and iron in most samples. Little if any enrichment in either titanium or manganese is apparent. Lead is present in the bulk rock at levels up to 140 mg/l, although in one clay-size fraction a value of 530 mg/l was attained.

Water Chemistry

Analyses of waters from the Energy Fuels Mine are presented in Table 5. These analyses are plotted on the vector diagram* in Figure 16. The vector diagram shows that certain types of waters are grouped together. The first group consists of D-6, CD-8, S-10, D-9, and Pond 1. All these waters, with the exception of Pond 1, are sodium bicarbonate ground waters. Pond 1, a surface sample upstream of the mine is a mixed cation (calcium-magnesium-sodium), bicarbonate water. All samples in this group have a low total dissolved solids (TDS) content.

The second group of waters consists of S-6, S-9, and D-14. Sample D-14 is a sodium-predominant mixed anion water (bicarbonate plus sulfate). Samples S-6 and S-9 are mixed cation-sulfate-predominant waters. All three waters have intermediate ionic strengths and TDS content. All three of these waters occurred in association with shales.

The third and final group consists of all remaining surface samples (P-2, P-3, spoils flume, and Stream 1) and the lysimeter samples (SL-3 and SL-4). These are mixed-cation, high-TDS sulfate waters. These surface samples are all at or downstream of the mine and both lysimeter samples were taken from the spoil piles.

Input Parameters

The following is a summary of the important parameters from the Energy Fuels Mine that represent inputs to the development of the predictive method:

Climate. Semi-arid conditions prevail and evaporation generally exceeds precipitation, but surpluses do occur during the spring of the year.

---

* For an explanation of the vector diagrams used in the report, see Section 8; Graphical Representation of Waters.

TABLE 5. WATER DATA
ENERGY FUELS MINE, COLORADO

Samples	Pond 1	Pond 2	Pond 3	Spoils Flume	Stream 1	Lysimeter SL-3	Lysimeter SL-4	Well S-6	Well S-9	Well S-10	Well D-6	Well CD-7	Well CD-8	Well D-9	Well D-14
Field Measurements															
Temperature (°C)	13.8	14.0	17.0	10.2	14.5	10.0	4.0	7.2	10.2	7.2	9.0	6.3	13.7	11.4	8.0
pH	9.2	8.1	6.2	8.4	8.0	7.7	6.5	7.4	7.2	7.6	7.9	10.0	7.7	9.6	6.5
Dissolved O_2 (mg/l)	14.0	21.0	0	16.0	10.0	3.0	0	14.0	11.0	8.0	14.0	13.0	9.1	0	0
Conductivity (μmhos)	450	1,860	2,400	1,750	2,000	2,100	1,700	1,180	1,380	710	800	240	450	780	880
Laboratory Measurements															
Temperature (°C)	13.8	14.0	17.0	10.2	14.5	10.0	4.0	7.2	10.2	7.2	9.0	6.3	13.7	11.4	8.0
pH	9.2	8.1	6.2	8.4	8.0	7.7	6.5	7.4	7.2	7.6	7.9	10.0	7.7	9.6	6.5
Total Dissolved Solids (mg/l)	416	2,546	3,058	2,475	2,444	3,000	2,448	1,568	1,710	798	795	318	450	860	1,086
Ca^{+2} (mg/l)	36.0	365.0	429.0	400.0	250.0	407.0	229.0	242.0	153.0	41.0	14.0	28.0	36.0	5.4	79.0
Mg^{+2} (mg/l)	37.0	127.0	151.0	187.0	229.0	176.0	122.0	105.0	106.0	20.0	8.0	15.0	19.0	1.2	24.0
Na^{+1} (mg/l)	33.0	30.0	30.0	38.0	134.0	200.0	371.0	59.0	223.0	200.0	286.0	18.0	108.0	271.0	237.0
K^{+1} (mg/l)	2.2	2.9	5.2	3.7	2.6	22.0	6.0	1.4	3.9	3.3	2.0	25.0	2.6	2.7	3.0
Fe° (mg/l)	<0.1	0.3	0.4	0.1	0.1	0.50	0.10	0.2	0.5	0.4	<0.2	<0.1	0.1	1.3	0.7
SO_4^{-2} (mg/l)	68	1,450	1,750	1,440	1,540	1,650	1,450	735	800	176	263	1,393	70	100	500
HCO_3^{-1} (mg/l)	141	273	141	296	544	271	219	384	547	571	490	269	312	543	454
CO_3^{-2} (mg/l)	53	2	0	0	0	0	0	0	0	0	0	5	0	48	0
Cl^{-1} (mg/l)	17	10	10	10	55	59	47	13	16	12	33	32	10	10	18

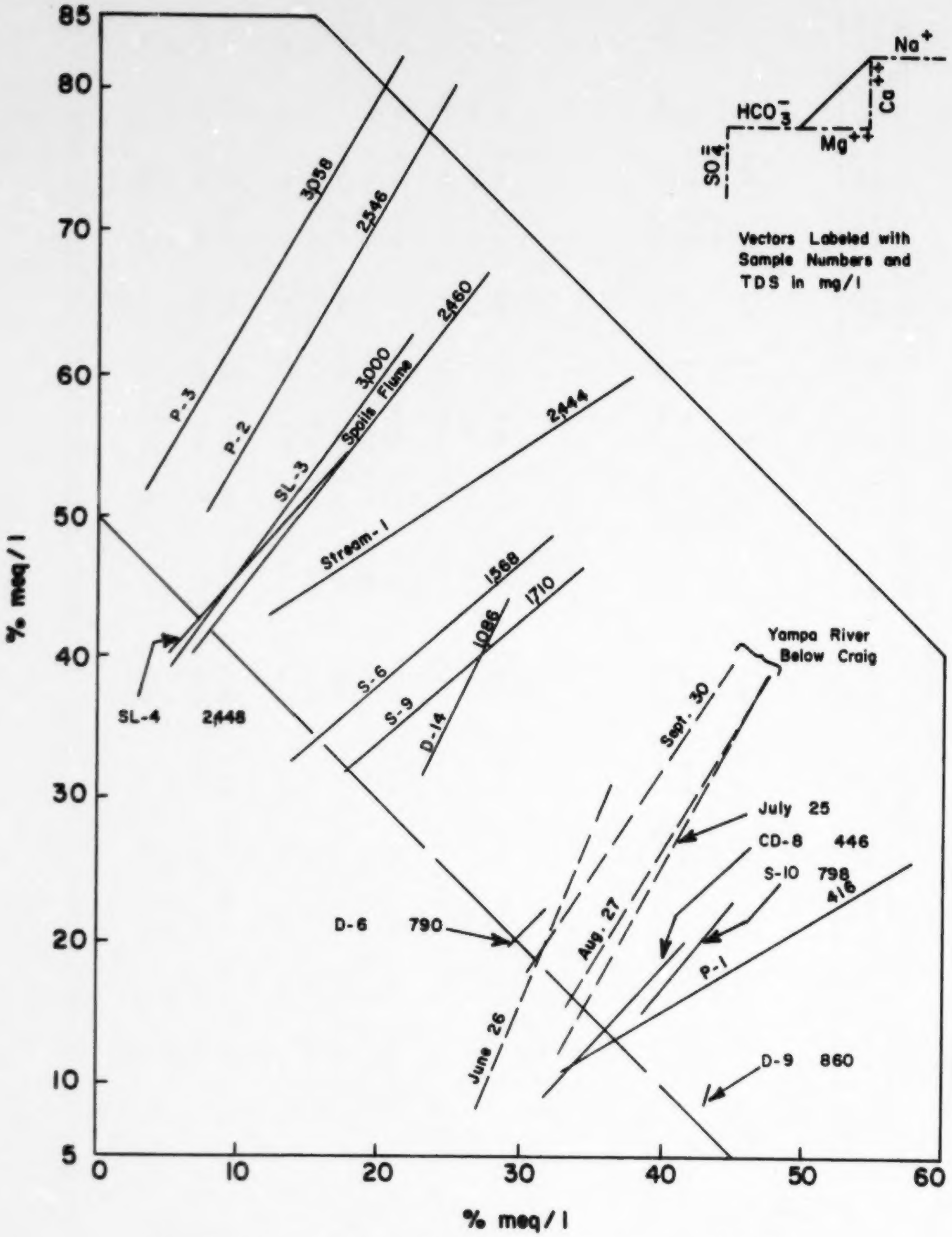


Figure 16. "Vector" diagram of water compositions. Energy Fuels Mine, Colorado. (Dashed lines from U.S.G.S. Water Resources Data for Colorado, 1975. Green River Basin. Analyses appear in Appendix Table C-9.)

Geology. The geology is structurally simple with gently dipping strata and no major faulting at the mine.

Hydrogeology. Both unconfined and confined ground-water conditions exist at the mine. The deeper, confined aquifers are in some cases flowing artesians.

Mineralogy. Carbonates present included dolomite, calcite, and siderite. Dolomite usually was more predominant than calcite, and small quantities of pyrite and gypsum were present. Kaolinite was the major clay mineral, although minor amounts of vermiculite and montmorillonite were present.

Water Chemistry. Deep artesian waters were generally sodium bicarbonate type with intermediate TDS. The shallow ground waters were calcium-bicarbonate-sulfate waters with a low TDS. Waters in contact with spoils material were highly mineralized, having TDS content approximately six times higher than surface water upstream of the mine. The predominant ions in these waters were calcium and sulfate.

EDNA MINE

The Edna Mine is located approximately 3 mi southeast of the Energy Fuels Mine. It is owned and operated by the Pittsburg and Midway Coal Co., a subsidiary of Gulf Oil Corp.

Topography in the area is similar to that at the Energy Fuels Mine, namely rolling hills interspersed with steep gullies and cliff areas. Two large streams provide drainage from the area; Trout Creek to the north, which flows northeast, and Oak Creek to the east, which flows almost due north in the mine area. Figure 11 shows the drainage pattern in the Edna Mine area.

Climate

The climate at the Edna Mine is not unlike that at the Energy Fuels Mine, except for a slightly greater amount of snowfall. This is due to the approximately 500-ft higher altitude at the Edna Mine and the generally more rugged terrain adjacent to the Edna Mine. Springs and seeps in this area tend to be perennial, and probably are attributed to the protracted melting season.

Geology

The location of the Edna Mine with respect to the Energy Fuels Mine places it in relatively the same geologic setting. The only major difference being that the Edna Mine is located approximately 70 ft higher stratigrapically than the Energy Fuels Mine. It occupies the east limb of the Argo syncline, which is a smaller structure within the Twentymile Park syncline. The sediments in this area are dipping approximately 10° to the west toward Trout Creek. The Wadge coal seam of the Williams Fork Formation is presently being extracted from this mine. Figure 17 shows an idealized block diagram of major geologic features at the Edna Mine, and Figure 18 shows a detailed description of core from Hole CD-1.

Sampling Points

Ground-water sampling sites at the Edna Mine were placed in accessible locations where the Lennox coal seam was last mined. Mining of the Lennox seam in this area was not complete because the drilling in the spoils often encountered undisturbed lenses of the Lennox coal. Figure 19 shows the location of sampling points, ground-water flow directions, and the drainage basin boundaries within the mine area. Field logs of the holes drilled are presented in Appendix A.

The holes drilled for ground-water sampling were located upgradient and downgradient from those points at the base of spoils from which springs issued. In addition, some holes were located upgradient from perennial ponds.

Samples of the ponds and of the springs were taken to provide background data on water quality upstream from its point of discharge, at the point of discharge, and at intermediate points.

Hydrogeology

In a related, but as yet unpublished report, McWhorter, et al. (3) described the hydrology of the Edna Mine area in some detail. McWhorter divided the mine into individual watersheds based on surface topography. Each of these watersheds was equipped with monitoring stations to determine the surface discharge (see Figure 20). Some of the same phenomena observed by McWhorter were also noted during the course of this investigation; namely, most of the precipitation on spoils is either evapotranspired, infiltrated, or ponded in depressions and later infiltrated, with little or no overland flow.

The recharge areas for ground water at the Edna Mine are similar to those for the Energy Mine; namely, the strata exposed between the Trout Creek and Twentymile sandstones. Shallow alluvial aquifers along Trout Creek would be recharged by the creek during times of high flow. Trout Creek has its headwaters to the north where it flows over Mancos Shale of Cretaceous Age. It is quite likely, therefore, that shallow alluvial waters

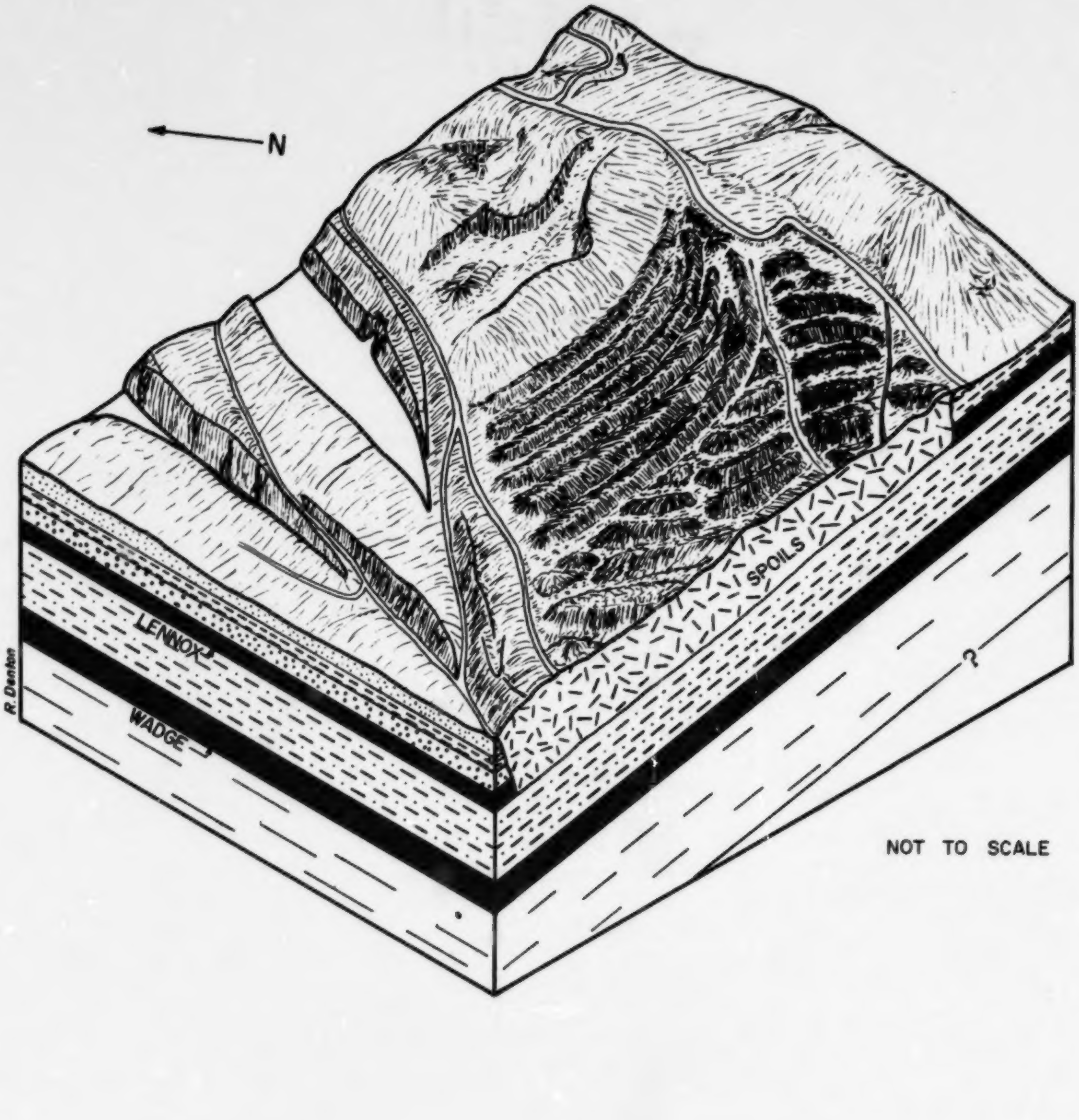

N
LENNOX
WADGE
SPOILS
?
NOT TO SCALE
R. Denton

Figure 17. Idealized block diagram showing major geologic features. Edna Mine, Colorado.

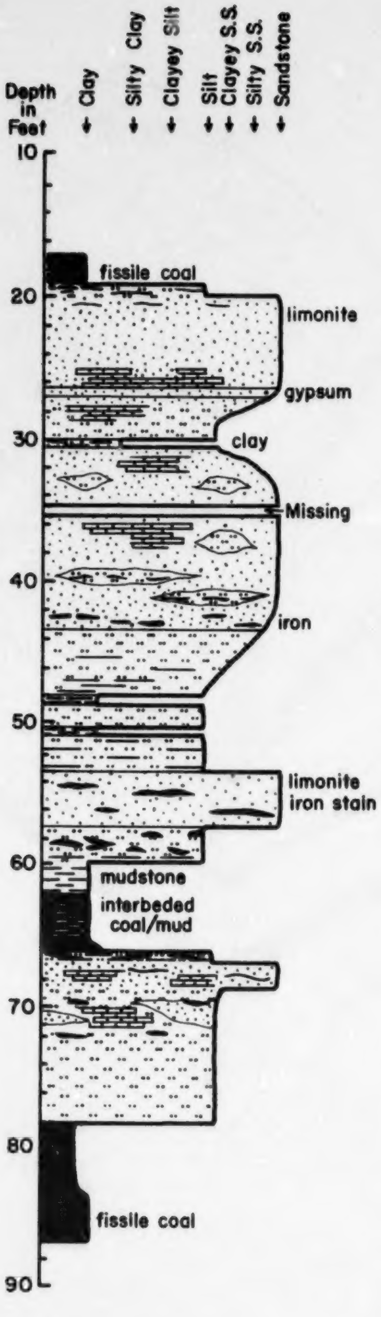

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
10
20
30
40
50
60
70
80
90
fissile coal
limonite
gypsum
clay
Missing
iron
limonite iron stain
mudstone
interbedded coal/mud
fissile coal

Figure 18. Detailed description of core from Hole CD-1. Edna Mine, Colorado.

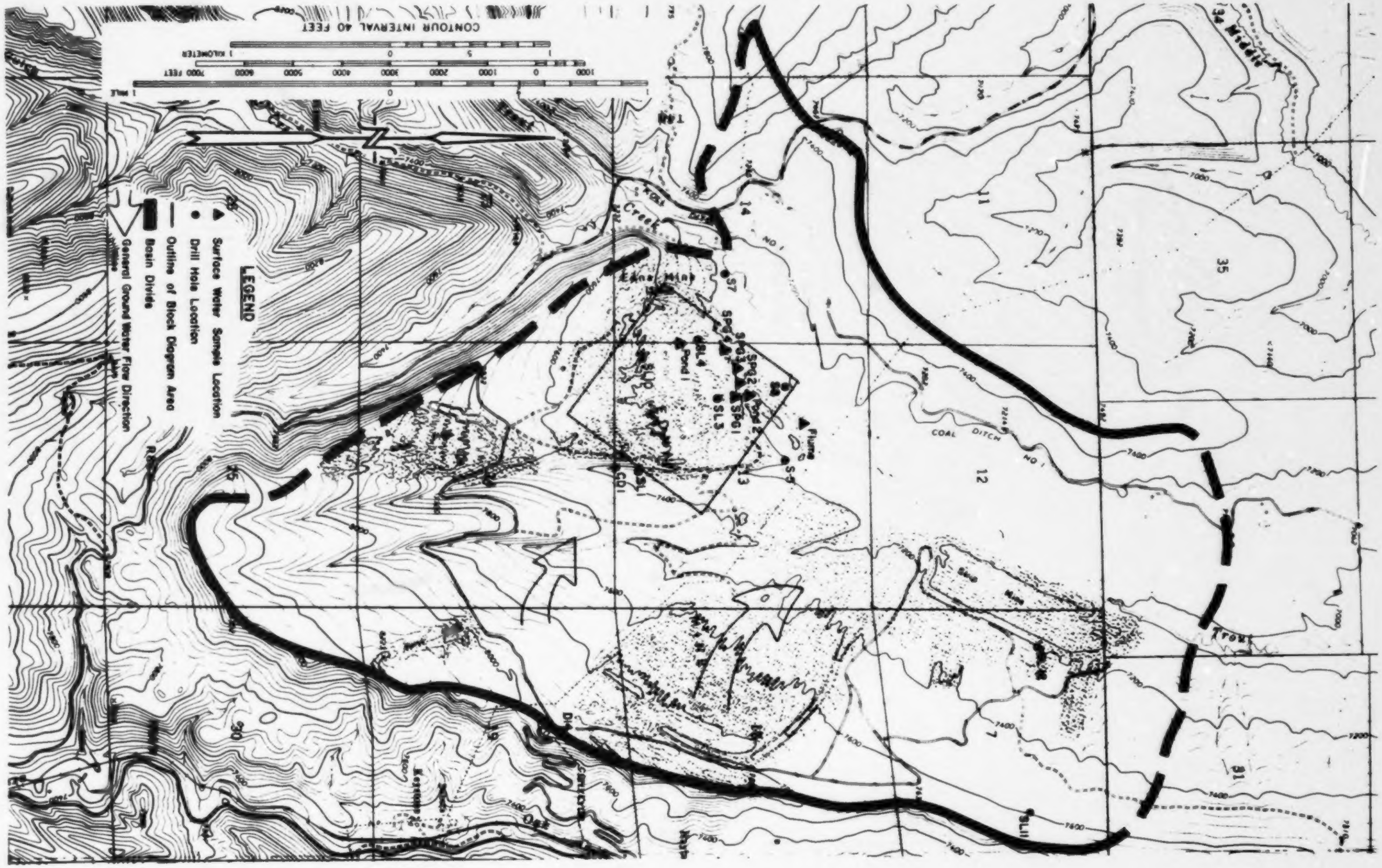

LEGEND
Surface Water Sample Location
Drill Hole Location
Outline of Block Diagram Area
Basin Divide
General Ground Water Flow Direction
CONTOUR INTERVAL 40 FEET
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 5 0 1 KILOMETER
1 0 1 MILE
Flume
S-5
Pond 2
SPG1
SPG2
SPG3
SPG4
SL3
SL4
Pond 1
SL10
SL1
CD1
S7
SL11
Edna Mine
Creek
COAL DITCH NO 1
34 Middle
Trout
35
11
12
14
13
31
7
25
26
30
19

Figure 19. Sample location map. Edna Mine, Colorado.

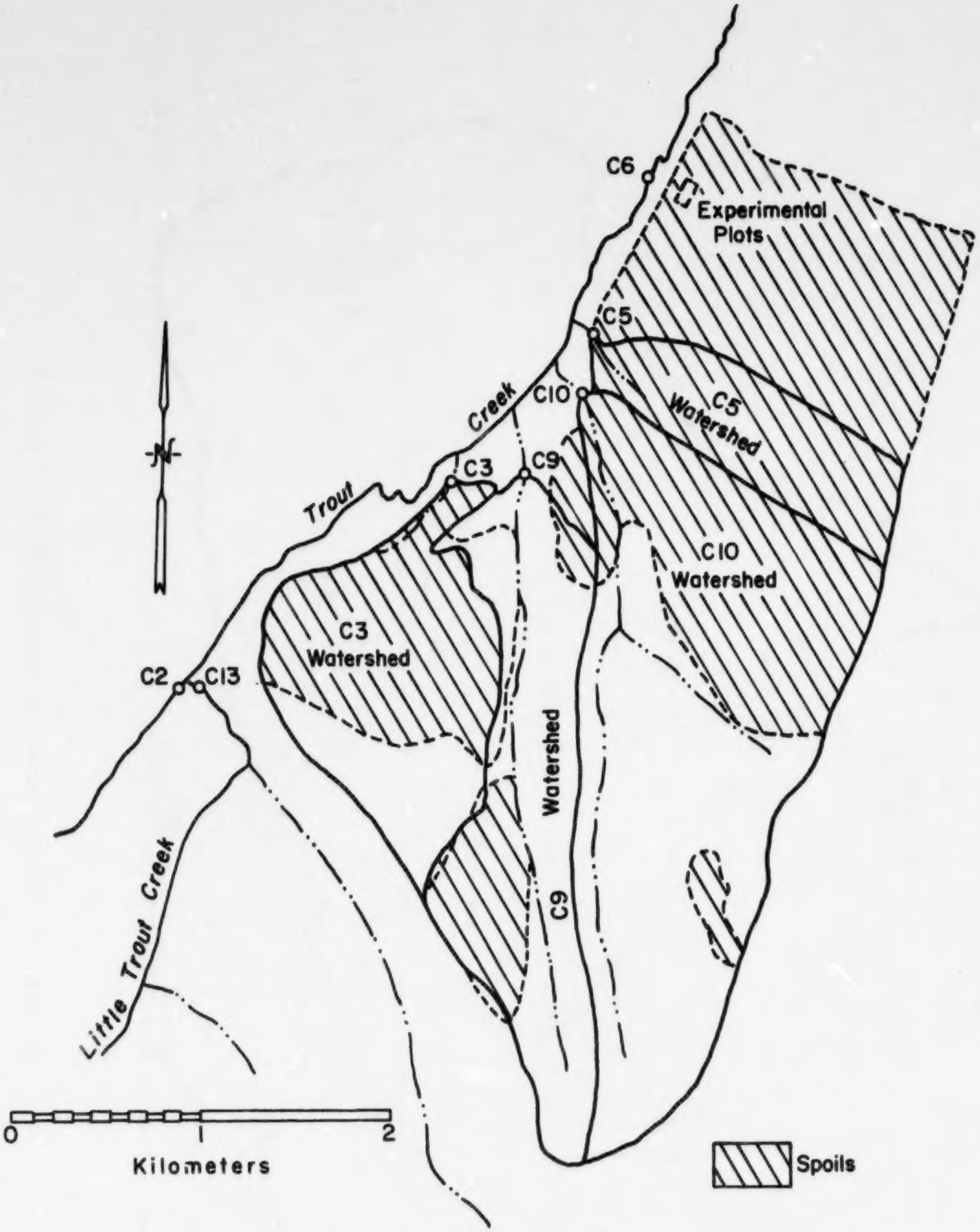

C6
Experimental Plots
C5
C10
C5 Watershed
Creek
Trout
C3
C9
C10 Watershed
C3 Watershed
C2
C13
Watershed
C9
Little Trout Creek
0
1
2
Kilometers
Spoils

Figure 20. Individual watersheds on the Edna Mine spoils, and discharge monitoring stations used by McWhorter. (After McWhorter) (3).

along Trout Creek will reflect to some degree the composition of the Mancos Shale. Trout Creek is the primary drainage from the Edna Mine area. The quality of the stream will not, however, have any effect on the groundwater quality of the overburden material currently being removed.

Areally, deep ground-water movement is from east to west toward the axis of the Twentymile syncline. More locally, shallower, ground-water movement would also be from east to west as evidenced by the springs and seeps along the bluff on the east side of Trout Creek.

Mineralogy

Lithologic examination of Core CD-1 revealed that it consisted of 39% sandstone, 35% siltstone, 6% shale, and 20% coal (see Figure 18). The sandstones and siltstones varied from non-calcareous to extremely calcareous. A sandstone stratum less than 1-ft thick at 27 ft was found to contain a large amount of gypsum. Iron staining was common throughout the section, but pyrite was not observed.

X-ray diffractometer scans of selected samples from Cores CD-1, S-10, and SL-12 revealed that the minerals present were quartz, feldspar, kaolinite, mica, calcite, dolomite, and gypsum (see Table 6). Some x-ray patterns revealed traces of possible pyrite. X-ray diffraction analysis revealed the main clay to be kaolinite with minor amounts of clay-mica, some quartz, and in one case, minor-to-trace amounts of vermiculite. Montmorillonite was not detected in any of the samples.

Water Chemistry

The water analyses are shown in Table 7, and a vector plot of this data is shown in Figure 21. Most of the ponds, springs, and lysimeter samples have very similar composition to the calcium-magnesium-sulfate type waters. The analysis of the water from Pond 1 must be discarded because of the extreme cation-anion imbalance; similarly, S-8, which could not be plotted on the vector diagram must also be discarded. Lysimeter Sample SL-12 is high in sodium and enriched in magnesium relative to calcium. No explanation for this anomalous composition is immediately apparent.

Samples S-5 and S-7, both from shallow alluvial aquifers, would be expected to have similar composition but do not. Sample S-7 is a calcium-magnesium bicarbonate and probably represents the pure alluvial aquifer. Sample S-5, on the other hand, could be explained by the mixing of sample S-7 and a surface water which would result in a calcium-magnesium-sulfate-bicarbonate with an intermediate TDS content as is observed.

TABLE 6. X-RAY DIFFRACTION DATA
EDNA MINE, COLORADO

	S-10			SL-12				CD-1	
	0-10'	20-30'	60-70'	0-5'	5-10'	10-15'	15-18'	21'	86.2'
Quartz	70-75	50	50-60	60	50	65	60	65-70	65-70
Feldspars	10-15	5	10	5	5	5	10	10	10
Kaolinite	15	15-20	20	10	10	10-15	10	10	10
Montmorillonite	--	-	--	--	10	--	--	--	--
Mica	--	--	--	--	5	--	5	5	5-10
Dolomite	--	10	--	5-10	5-10	5-10	5-10	--	--
Calcite	--	5-10	10	3-5	5	5	Tr	--	--
Siderite	--	--	--	--	--	--	--	--	--
Gypsum	--	5-10	--	--	--	--	--	--	--
CLAY FRACTION (<2μ)									
Wt % of Total	0.13	0.14	0.12	0.16	0.16	0.18	0.12	0.06	0.17
Kaolinite	M	M	M	m	m	M	M	M	M
Illite	m	m	m	m	m	m	m	m	m
Montmorillonite	--	Tr	Tr	--	--	--	--	--	--
Vermiculite	--	Tr	Tr	Tr	Tr	Tr	Tr	--	m-Tr

ND -- not determined

P -- predominant (est. +80%)

M -- major (est. 40-80%)

m -- minor (est. 10-40%)

Tr -- trace (est. 1-10%)

TABLE 7. WATER DATA
EDNA MINE, COLORADO

Samples	Pond 1	Pond 2	Pond 3	Spring 1	Spring 2	Spring 3	Spring 4	Lysimeter SL-3	Lysimeter SL-10	Lysimeter SL-12	Well S-5	Well S-7	Well S-8
Field Measurements													
Temperature (°C)	25.0	24.0	16.8	9.8	10.0	10.3	11.5	8.5	12.0	7.0	10.0	8.0	14
pH	8.2	8.3	7.3	7.2	7.1	7.6	7.4	6.8	6.9	8.4	7.0	7.3	7.1
Dissolved O_2 (mg/l)	9	14	0	15	17	15	15	4	2	2	3	5	8
Conductivity (μmhos)	2,380	2,170	2,180	1,625	1,640	1,810	2,000	1,940	2,400	4,050	1,220	140	560
Laboratory Measurements													
Temperature (°C)	25.0	24.0	16.8	9.8	10.0	10.3	11.5	8.5	12.0	7.0	10.0	8.0	14.0
pH	8.2	8.3	7.3	7.2	7.1	7.6	7.4	6.8	6.9	8.4	7.0	7.3	7.1
Total Dissolved Solids (mg/l)	2,740	2,226	2,574	2,480	2,456	2,782	2,810	2,920	2,850	5,440	1,550	124	608
Ca^{+2} (mg/l)	500	386	415	407	415	472	486	440	420	170	276	26	276
Mg^{+2} (mg/l)	150	113	151	169	150	178	157	182	111	158	92	10.7	29
Na^{+1} (mg/l)	26.0	25.0	22.0	11.4	13.7	14.0	25.0	26.0	86.0	1,140.0	24.0	4.8	14.0
K^{+1} (mg/l)	4.7	2.7	2.6	2.2	2.6	2.2	3.2	4.0	5.0	38.0	4.0	1.3	6.6
SO_4^{-2} (mg/l)	230	1,488	1,250	1,650	1,563	1,563	1,725	1,875	1,634	2,975	775	25	1,530
HCO_3^{-1} (mg/l)	128	53	107	168	247	163	162	137	253	730	410	116	181
CO_3^{-2} (mg/l)	0	2	0	0	0	0	0	0	0	0	0	0	0
Cl^{-1} (mg/l)	13	14	13	10	10	10	12	11	47	22	14	4	14

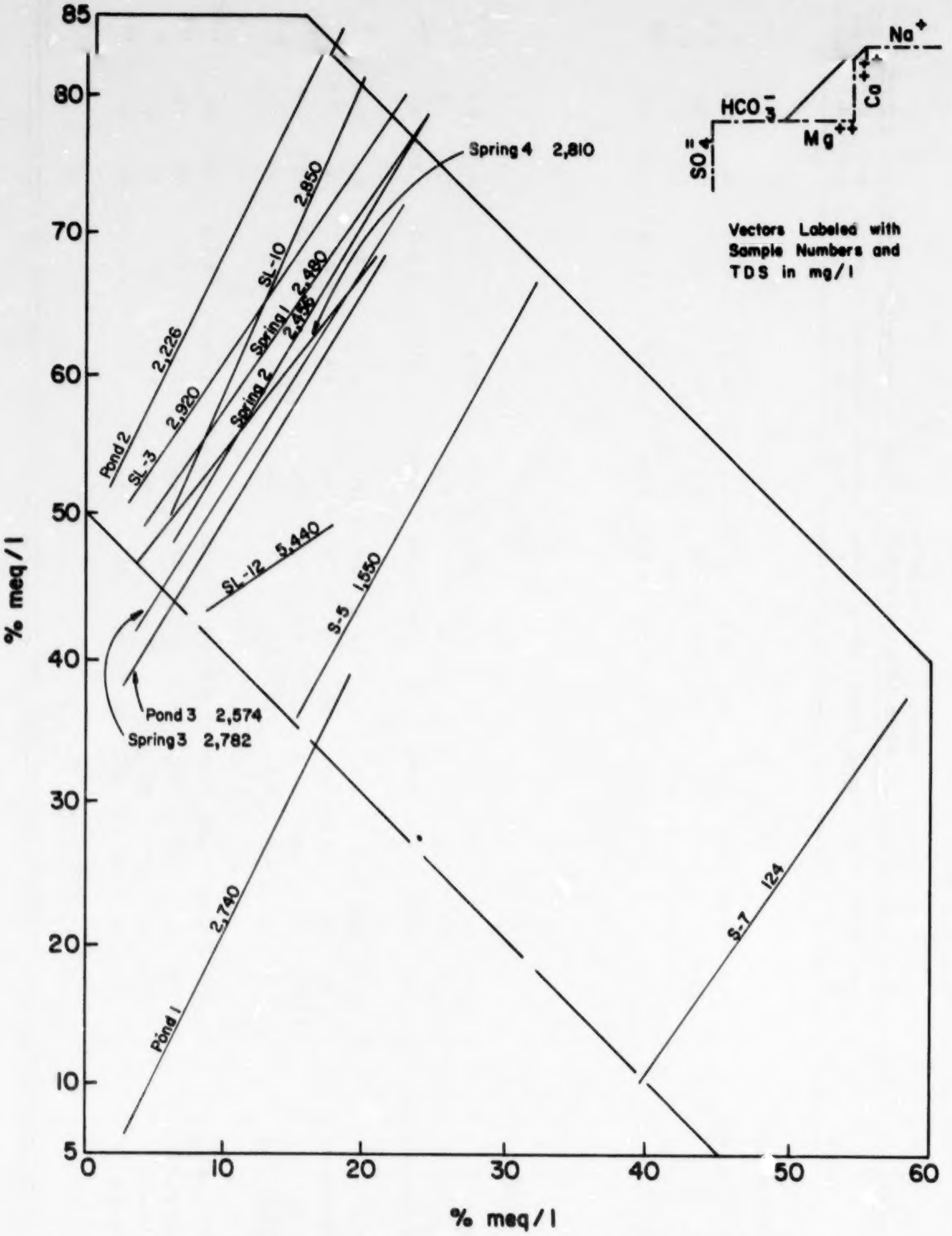


Figure 21. "Vector" diagram of water compositions. Edna Mine, Colorado.

Input Parameters

The following is a summary of the important parameters from the Edna Mine that represent inputs to the development of the predictive method:

Climate. Semi-arid conditions prevail and evapotranspiration generally exceeds precipitation, but surpluses do occur during the spring of the year.

Geology. The geology is structurally uncomplicated. No faults or fault zones were noted.

Hydrogeology. Only unconfined ground-water conditions were observed at the mine.

Mineralogy. Calcite, dolomite, and gypsum were the principal reactive minerals observed. Traces of pyrite were detected, but iron staining was common throughout the section indicating that pyrite may have been present originally.

Water Chemistry. Water from an upstream shallow alluvial aquifer was found to be very low in TDS and contained calcium-magnesium bicarbonate as the major constituents. The surface waters from the spoils all contained calcium, magnesium, and sulfate as the principal ions, and they were high in TDS.

McKINLEY MINE

The McKinley mine is owned and operated by the Pittsburg and Midway Coal Mining Co., a subsidiary of Gulf Oil Corp. The mine is located approximately 30 mi north and west of Gallup, New Mexico, and approximately 5 mi east of Window Rock, Arizona. The mine is situated on the western margin of the San Juan Basin and covers approximately 32,000 acres, portions of which are owned by the Federal Government, the Pittsburg and Midway Coal Co., and the Navajo Nation.

The mine occurs in an area of low-lying mesas and gullies with a maximum relief of approximately 250 to 300 ft. Drainage from and through the mine area is via the Tse Bonita Wash which drains to the southwest through the active mine area (see Figure 22). The Tse Bonita Wash is an intermittent stream that flows only during the sporadic thunderstorms occurring throughout the area.

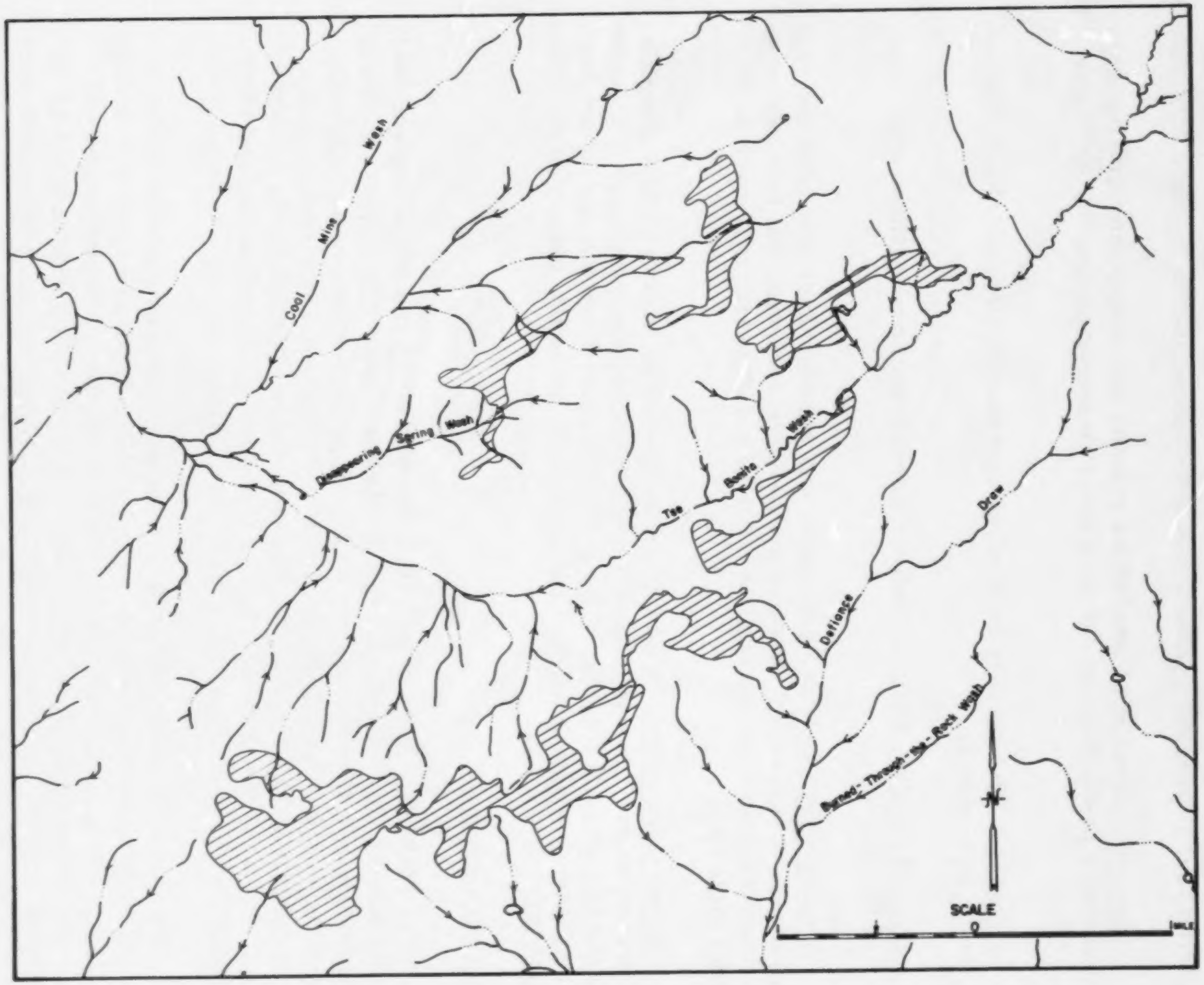

Coal Mine Wash
Disappearing Spring Wash
Tse Bonito Wash
Defiance Draw
Burned-Through-the-Rock Wash
N
SCALE
0
1 MILE

Figure 22. Surface drainage in the vicinity of the McKinley Mine, New Mexico.

Climate

The area in the vicinity of Gallup and the McKinley Mine is arid and receives only 8 to 12 in. of precipitation per year, most of which falls during the summer as thunderstorms. No perennial streams exist in the area investigated. Annual temperatures are moderate, with a mean January temperature of 26°F and a mean July temperature of 68°F. The average annual temperature is 49.7°F.

Evapotranspiration calculations for the towns of Zuni, San Juan, and Navajo show annual deficits of soil moisture of 13.9, 11.1, and 16.57 in., respectively. June and July show the greatest monthly deficit, 36.7 and 36.6 in. It is clear that precipitation will have little or no effect on groundwater quality in this area unless an attempt is made to contain the sudden runoffs of summer thunderstorms, as is done at the McKinley Mine. Even then, the infiltration of impounded water is probably very slow, as well as areally minimal, and its effects can therefore be considered negligible.

Geology

The McKinley Mine, which is situated in the Gallup coal field, lies in an area on the western margin of the San Juan Basin known as the Gallup Sag. The area is composed of gently dipping to relatively flat-lying sediments bounded on the east and on the west by monoclinal structures, with the Zuni and Defiance uplifts dipping toward the basin center. Rocks outcropping in the Gallup Sag are Cretaceous and Tertiary, comprised of the Mancos Shale, Mesaverde Group, and some later Tertiary sandstones and shales.

Coal is mined from five commercial coal seams found in the Upper Cretaceous Gibson Member of the Crevasse Canyon Formation and the Cleary Member of the Menefee Formation. Both formations are of the Mesaverde Group. The Crevasse Canyon and Menefee Formations are separated in the southern part of the San Juan Basin by the Point Lookout Sandstone, which does not appear in the Gallup Sag. For this reason, the two members are normally referred to as the Gibson Member of the Menefee Formation, in the Gallup field (11).

The various lithologic constituents of the Gibson Member are very lenticular and difficult to correlate. Observation on highwall pits and drill holes revealed shales and sandstones alternating with coal seams of various quality and thickness. The rocks in each of the pits show considerable rolling structure and lenticularity, and dip generally to the southeast at angles of approximately 5°. Contacts between sandstone and shales are gradational in many places. Sandstone units are medium-grained with thin layers of organic material and are generally thicker in exposed highwall faces than the shale layers. Much of the shale is either poorly consolidated or weathered, and some calcareous claystones with calcite vugs were observed in the Section 5 pit. Iron staining was noted in shales above and below coal seams.

Figure 23 presents the major geologic features of a section of the McKinley Mine. Due to the lenticularity of the rocks, individual lithologic units cannot be accurately correlated over the entire mine area. Field logs of all holes drilled are presented in Appendix A. Figures 24 through 26 present a detailed lithologic description of Holes EMK-1, EMK-6C, and EMK-11.

Sampling Points

Water at the McKinley Mine was found to be standing in the mine pits of Sections 5, 32, and 33. Discussion with mine personnel indicated that this water was accumulated from the runoff of thunderstorms during the summer and snowmelt in the spring. These ponds thus acted as recharge basins to the underlying spoils material. Locations of sampling points in the McKinley Mine area are shown in Figure 27.

Lysimeters were placed in the saturated zone of the spoils to collect water moving from the pits through the spoils. Water samples were also collected from the pits to allow comparisons of water quality before and after movement through the spoils. Of the holes drilled at the McKinley Mine, five encountered water: EMK-5L, 7L, 8, 10, and 13L.

Hydrogeology

Ground-water recharge to the McKinley Mine area is believed to result primarily from the Chuska Mountains to the north and the Defiance uplift to the west. Direct summer precipitation is not likely to contribute significantly to recharge in the mine area. Additional recharge probably occurs along the flanks of the basin where the beds are tilted, exposed, and covered with vegetation at altitudes of 6,500 ft or greater. The Cretaceous rocks with which surface waters would come into contact prior to reaching the mine area are those of the Menefee Formation.

Aquifers in the Menefee Formation are thin, lenticular, and tongue out to the northeast; therefore, movement of water toward the center of the San Juan Basin is restricted. These aquifers are likely to be imperfectly interconnected, thus creating a multiple hydraulic system in the western part of the San Juan Basin (25). The Dalton Sandstone Member of the Crevasse Canyon Formation, in addition to deeper underlying sandstone, provide sources of low-volume ground water. Ground-water movement in these units, in the vicinity of the mine, is likely to be toward the south (see Figure 27).

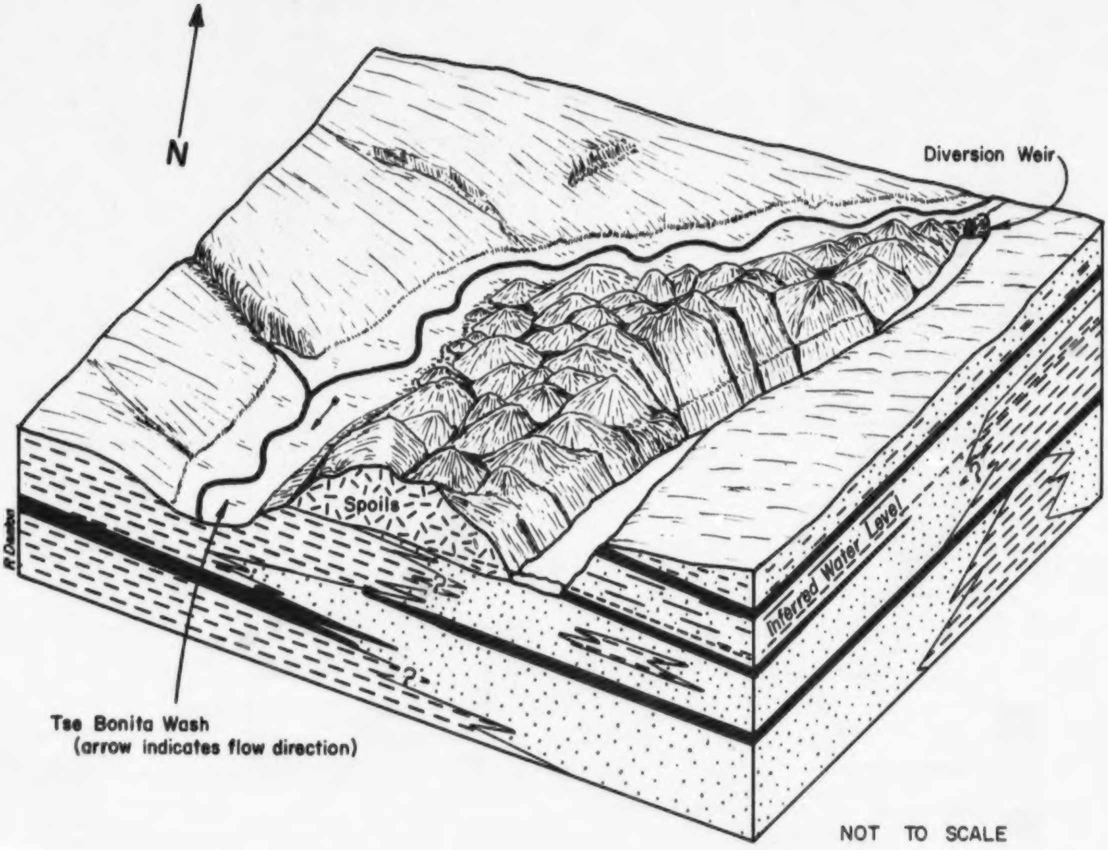

N
Diversion Weir
Spoils
Inferred Water Level
?
Tse Bonita Wash
(arrow indicates flow direction)
NOT TO SCALE

Figure 23. Idealized block diagram showing major geologic features, McKinley Mine, New Mexico.

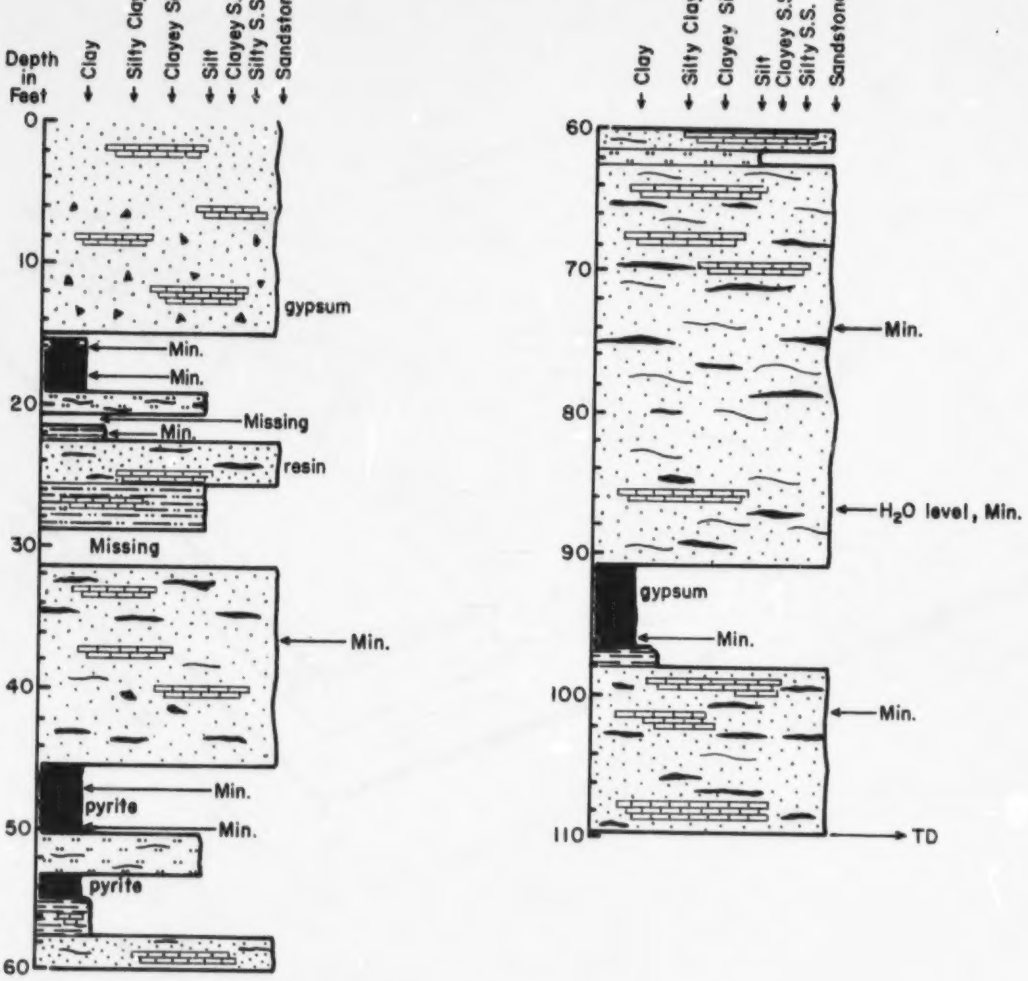

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
30
40
50
60
gypsum
Min.
Min.
Missing
Min.
resin
Missing
Min.
Min.
pyrite
Min.
pyrite
60
70
80
90
100
110
Min.
H2O level, Min.
gypsum
Min.
Min.
TD

Figure 24. Detailed description of core from Hole EMK-1. McKinley Mine, New Mexico.

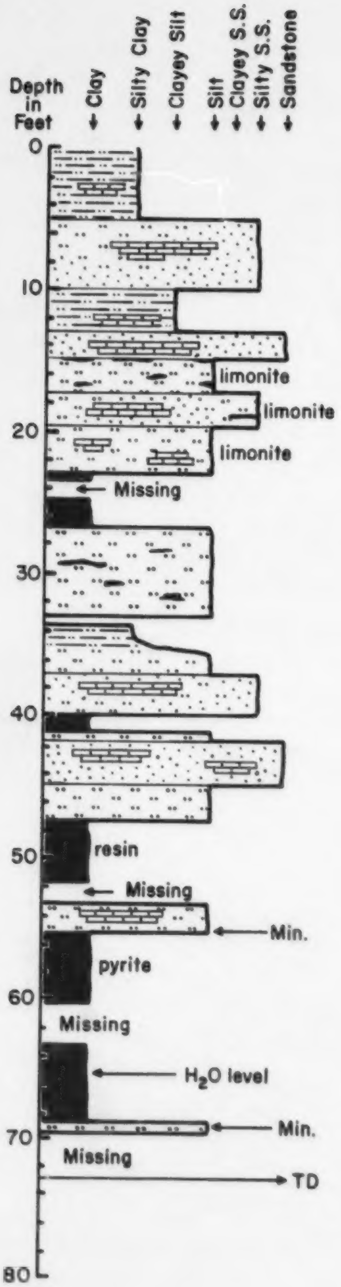

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
30
40
50
60
70
80
limonite
limonite
limonite
Missing
resin
Missing
Min.
pyrite
Missing
H_2O level
Min.
Missing
TD

Figure 25. Detailed description of core from Hole EMK-6C. McKinley Mine, New Mexico.

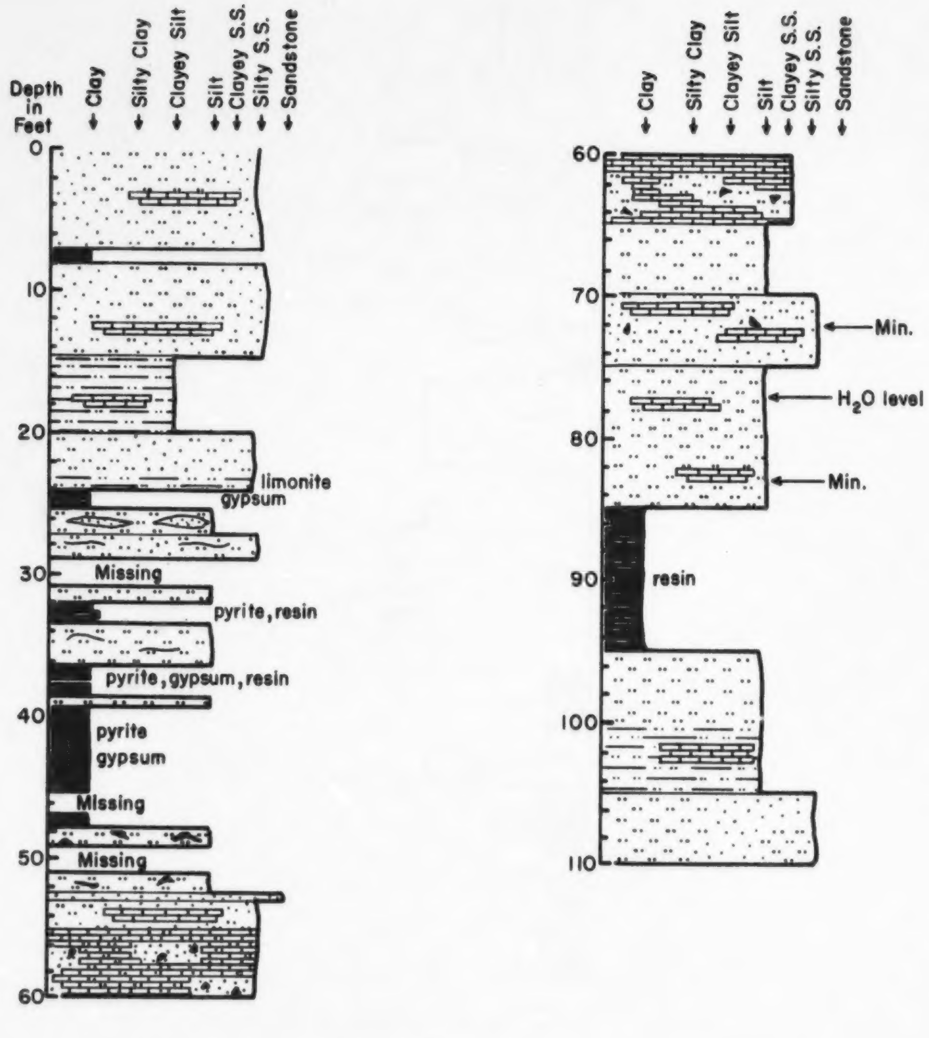

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
limonite
gypsum
30
Missing
pyrite, resin
pyrite, gypsum, resin
40
pyrite
gypsum
Missing
50
Missing
60
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
60
70
Min.
H_2O level
80
Min.
90
resin
100
110

Figure 26. Detailed description of core from Hole EMK-11. McKinley Mine, New Mexico.

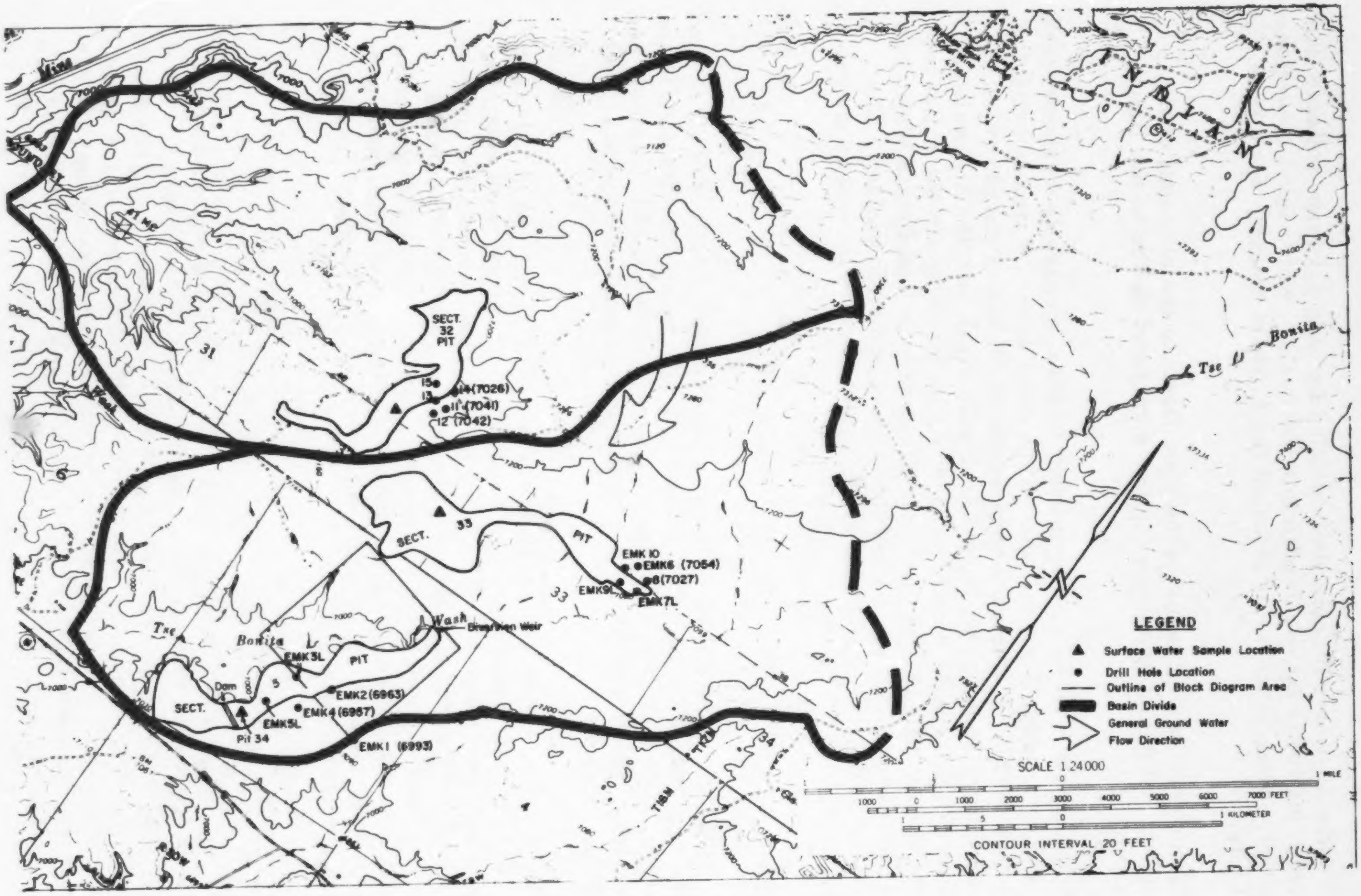

LEGEND
▲ Surface Water Sample Location
● Drill Hole Location
Outline of Block Diagram Area
Basin Divide
General Ground Water Flow Direction
SCALE 1:24000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER
CONTOUR INTERVAL 20 FEET
SECT. 32 PIT
15
13
14(7026)
11 (7041)
12 (7042)
SECT. 33 PIT
EMK 10
EMK6 (7054)
8(7027)
EMK9L
EMK7L
SECT. 5 PIT
Dam
EMK3L
EMK2(6963)
EMK4(6957)
EMK5L
Pit 34
EMK1 (6993)
Tse Bonita Wash
Diversion Weir
31
33
34
T16N
R20W

Figure 27. Sample location map. McKinley Mine, New Mexico.

Depths-to-water in open wells drilled for this program indicate that waters from pit areas move downdip into the coals. Water level elevations are generally lower in the wells situated the farthest downdip away from the highwall pits.

Ground-water discharge in the area flows to the alluvium of the Puerco River and possibly across the low structural divide to the Black Mesa Basin (25).

Surface water flows in intermittent washes, generally westward into Black Creek approximately 8 mi west of the mine area. Water is collected in the Section 5 pit by a diversion weir at the north end of the pit which diverts flood waters and run-off from Tse Bonita Wash into the highwall pit (see Figure 27). An earth dam is present in the pit to retain the collected water. Section 32 and 33 pits intersect a tributary to Tse Bonita Wash. In all cases, the flow in the washes is intermittent and often violent. The southwest end of the drainage basin in which the mine is located is shown in Figure 27.

Mineralogy

A lithologic examination of the cores from Holes 1, 6, and 12 showed an average percentage of the components to be approximately 40% sandstone, 20% siltstone, 20% coal, and 20% clay, with most of the clastic fractions being calcareous. Small quantities of both pyrite and gypsum were observed throughout the core.

The results of selected x-ray diffractometer scans are given in Table 8. Calcite and siderite are the dominant carbonates, with dolomite generally being rare to absent. The predominant clay is kaolinite, although clay-mica and montmorillonite are generally present in small amounts. Gypsum was positively identified in several samples. Other sulfates tentatively identified in some samples, included anhydrite, epsomite, and rozenite. Both epsomite and rozenite are almost certainly secondary, and both are readily soluble in water.

Water Chemistry

The majority of McKinley Mine surface and ground waters contain predominant sodium and sulfate, as shown in Figure 28 and Table 9. Several well samples, however, are of the sodium-bicarbonate type (see EMK-1, 6, and 8). Arranging all these sodium-bicarbonate waters on the basis of ionic strength, wells completed in sandstone are the weakest and are of the sodium-bicarbonate type. All other samples reflect water movement through or near coals and, as such, are sulfate rather than bicarbonate types.

TABLE 8. X-RAY DIFFRACTION DATA
McKINLEY MINE, NEW MEXICO

	Hole 1					Hole 2	Hole 3	Hole 4		Hole 5	Hole 6		Hole 7	Hole 8	Hole 11		Hole 12		Hole 13	Hole 14	Hole 15	Pit	Pit
	16'	22'	74'	87'	101'	30-35'	65-70'	20-25'	45-50'	40-50'	55'	69'	50-55'	30-35'	70-75'	80-85'	74'	75'	30-35'	55-60'	50'	32	34
Quartz	40	50	40	40	50	40	50	50	50	45	50	50	55	50	35	50	50	50	45	50	50	60	65
Feldspars	5-10	20	25	15	10	25	10	20	30	10	5	15	10	5	25	10	20	25	5-20	10	5-10	20	15
Kaolinite	20	15	20	5	15	25	25	20	15	15	15-20	20	20	40	10	15-20	20	20	15	10-15	15	15	10-15
Montmorillonite	10	--	5	?	--	--	--	--	--	--	--	Tr	--	--	--	--	--	--	--	--	Tr	Tr	--
Mica	20	5-10	5	5	10	2	10	5	5	--	5	5	--	--	--	10	5	5	Tr	5	5-10	5	Tr
Dolomite	--	--	?	?	--	?	2	--	--	--	--	--	--	--	--	--	--	--	--	Tr	--	--	--
Calcite	--	1	5	--	20	5	3	--	--	5	5	5	--	--	15	--	Tr	--	--	--	Tr	--	Tr
Siderite	--	5	5	35	?	5	5	Tr	--	Tr	--	5	--	--	10	?	5	5	--	--	--	--	--
Gypsum	--	--	--	--	--	--	--	--	--	5-10	5	Tr	--	--	--	--	--	--	10	--	5	--	--
Anhydrite	--	--	--	--	--	--	--	--	--	?	--	--	--	--	--	--	--	--	--	--	--	--	--
Epsomite	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rozenite	--	--	--	--	--	--	--	--	--	?	--	--	--	--	--	--	--	--	--	--	--	--	--
Pyrite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Magnetite	--	?	--	--	--	?	--	--	--	--	--	Tr	--	--	--	--	--	--	--	--	--	--	--
CLAY FRACTION (<2μ)																							
Wt % of Total	ND	ND	6	ND	4	14	26	24	ND	16	19	12	10	26	11	39	7	ND	25	27	11	18	11
Kaolinite	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	--	M	M	M	M	M
Illite	Tr	m	m	m-Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	m	Tr	Tr	Tr	Tr	m	--	m	m	m-Tr	m	m-Tr
Montmorillonite	Tr	Tr	Tr	Tr	Tr	--	Tr	Tr	Tr	Tr	Tr	Tr	m	Tr	Tr	--	--	--	Tr	--	Tr	--	--
Vermiculite	--	m	Tr	Tr	--	--	m	Tr	m	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	--	Tr	--	--	Tr	--

ND -- not determined P -- predominant (est. +80%) M -- major (est. 40-80%) m -- minor (est. 10-40%) Tr -- trace (est. 1-10%)

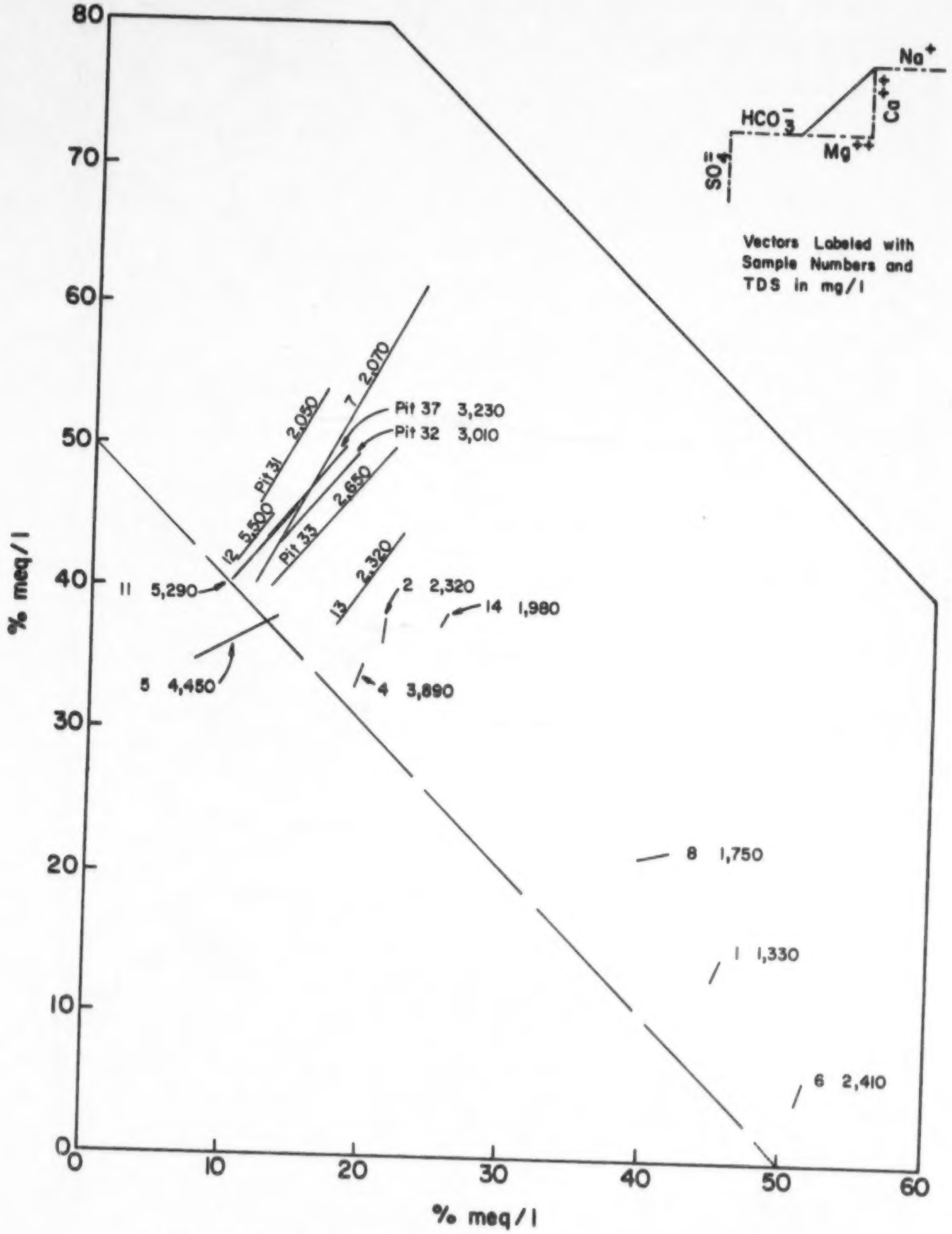


Figure 28. "Vector" diagram of water compositions. McKinley Mine, New Mexico.

TABLE 9. WATER DATA
McKINLEY MINE, NEW MEXICO

Samples	Pit 32	Pit 33	Pit 34	Pit 37	Well 1	Well 2	Well 4	Well 5	Well 6	Well 7	Well 8	Well 11	Well 12	Well 13	Well 14
Field Measurements															
Temperature (°C)	8.5	9.5	10.0	4.0	10.5	8.5	12.5	13.0	11.0	12.5	12.5	11.0	9.5	7.5	12.0
pH	8.2	8.1	8.2	8.2	7.7	7.75	6.8	7.0	8.5	6.5	7.0	6.5	7.0	7.4	8.1
Dissolved O_2 (mg/l)	2	8	2	2	2	3	2	2	2	4	2	3	3	4	2
Conductivity (μmhos)	2,325	2,300	1,800	2,450	1,475	2,400	4,000	5,500	1,625	2,000	2,000	4,700	3,800	2,225	2,300
Laboratory Measurements															
Temperature (°C)	8.5	9.5	10.0	4.0	10.5	8.5	12.5	13.0	11.0	12.5	12.5	11.0	9.5	7.5	12.0
pH	8.2	8.1	8.2	8.2	7.7	7.75	6.8	7.0	8.5	6.5	7.0	6.5	7.0	7.4	8.1
Total Dissolved Solids (mg/l)	3,010	2,650	2,050	2,450	1,330	2,320	3,890	4,450	2,410	2,000	1,750	5,290	5,500	2,320	1,980
Ca^{+2} (mg/l)	121.0	156.0	87.9	121.0	12.0	18.8	38.2	273.0	14.9	284.0	49.8	157.0	105.0	92.2	11.4
Mg^{+2} (mg/l)	58.3	78.8	30.2	60.3	4.1	5.4	12.6	11.6	4.33	94.5	13.8	85.4	35.9	38.9	3.38
Na^{+1} (mg/l)	729	540	453	757	472	742	1,320	1,390	553	273	532	1,390	1,490	680	596
K^{+1} (mg/l)	12.1	9.61	9.03	10.6	5.51	4.28	6.92	18.6	4.43	14.7	7.19	11.6	10.1	13.9	3.25
$\mathring{Fe}$ (mg/l)	<0.1	0.069	<0.1	0.3	<0.1	0.3	0.4	0	9.5	0.332	7.1	1.0	6.5	0	3.7
SO_4^{-2} (mg/l)	1,740	1,450	1,180	1,840	271	1,187	1,930	2,800	107	1,310	509	2,940	2,940	1,350	967
HCO_3^{-1} (mg/l)	660	590	390	610	1,170	854	1,380	760	1,560	480	1,180	910	910	810	810
CO_3^{-2} (mg/l)	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0
Cl^{-1} (mg/l)	60	40	30	50	30	50	50	80	20	50	20	90	40	70	20

The predominance of sodium over calcium or magnesium can be attributed to the large amounts of clay encountered in the overburden and the paucity of carbonates. Calcium and magnesium released into the waters by the dissolution of calcite and dolomite are ion-exchanged by the abundant clays which release sodium.

Input Parameters

The following is a summary of the important parameters from the McKinley Mine that represent inputs to the development of the predictive method:

Climate. Low precipitation and high evapotranspiration is characteristic of the area.

Geology. The geologic structure of the mine may be described as simple although, because of lenticularity of beds, the stratigraphy is complex.

Hydrogeology. No extensive aquifer systems were encountered in the mine area. Surface water infiltration provided the primary water-mineral interaction.

Mineralogy. The most significant feature of the mineralogy is the presence of readily soluble sulfate minerals containing calcium, magnesium, or iron. Pyrite is present in small amounts. Carbonates are also present and exceed the amount of pyrite.

Water Chemistry. Surface waters and ground waters occurring in association with coal aquifers are generally sodic, usually with high sulfate. Sodium-bicarbonate ground waters were found in association with non-coal aquifers.

MEDICINE BOW MINE

The Medicine Bow Mine is operated by the Medicine Bow Coal Co., a joint venture of Hanna Basin Coal Co. and Dana Coal Co. The Hanna Basin Coal Co. is a subsidiary of Rocky Mountain Energy Co., a subsidiary of Union Pacific Land Resources Co. The Dana Coal Co. is a subsidiary of Arch Minerals Corp. Because the mine has been operating only since 1975, the spoiled areas are relatively new, and provide the time factor in data evaluation.

The Medicine Bow Mine is located in the Hanna Basin of south-central Wyoming. The basin is an intermountain structural feature approximately 35 by 20 mi. The mine is situated immediately north of the town of

Hanna and approximately 4 mi east of the Seminoe Reservoir.

Topographically, the area consists of undulating hills to areas of ridges and gullies that tend to be elongated northwest-southeast. The principal drainage from the mine area is provided by the intermittent streams Middle Ditch and Big Ditch which flow northwestward to the Seminoe Reservoir and ultimately to the Platte River (see Figure 29).

Climate

The climate in the vicinity of Medicine Bow is semi-arid. Temperatures average 43.3°F annually with widely varying extremes. Mean monthly maximum and minimum temperatures range from 30°F to 12°F in January, and from 92°F to 53°F in July. Snowmelt and rain in April, May, and June account for nearly half of the mean annual precipitation of about 12 in. High winds are common in the Hanna Basin due to its high elevations and low rolling hills as well as the paucity of trees. The average annual wind speed ranges from 12 to 14 mph.

Calculations of potential evapotranspiration and actual evapotranspiration from Saratoga, Wyoming, approximately 40 mi south of Hanna, show that a surplus of soil moisture occurs at no time during the year. The summer and early fall months show soil moisture deficits ranging from 0.5 in. in October to 4.0 in. in July. Total annual evapotranspiration was calculated to be 9.5 in., while the annual total deficit is 10.1 in., leaving a 0.6 in. deficit for the year. Slopes facing south are more subject to the summer heat and perennial winds than north-facing slopes, therefore offering greater evapotranspiration and a minimum of vegetation (26).

Geology

The Medicine Bow Mine lies near the western margin of the Hanna Basin. Coal in the Medicine Bow Mine is extracted from five commercial seams in the Ferris Formation, which is comprised of sediments ranging in age from Late Cretaceous to Paleocene. The entire formation is approximately 6,500 ft in thickness, of which approximately 1,100 ft are Cretaceous.

The Ferris Formation consists of shale, mudstone, siltstone, and fine-to-coarse grained sandstones with as many as 45 subbituminous coal seams (16). All units are lenticular, and correlation of seams over large distances is not reliable (26). The rocks of the Ferris Formation dip gently to the east, toward the center of the basin, with an average local dip of approximately 8°. Several major north-northeast trending faults appear 2 to 3 mi north of the mine area. Only one major normal fault with a displacement of 70 ft was encountered in the study area. This fault defines the eastern limit of the mine operation (see Figure 30). Numerous other small

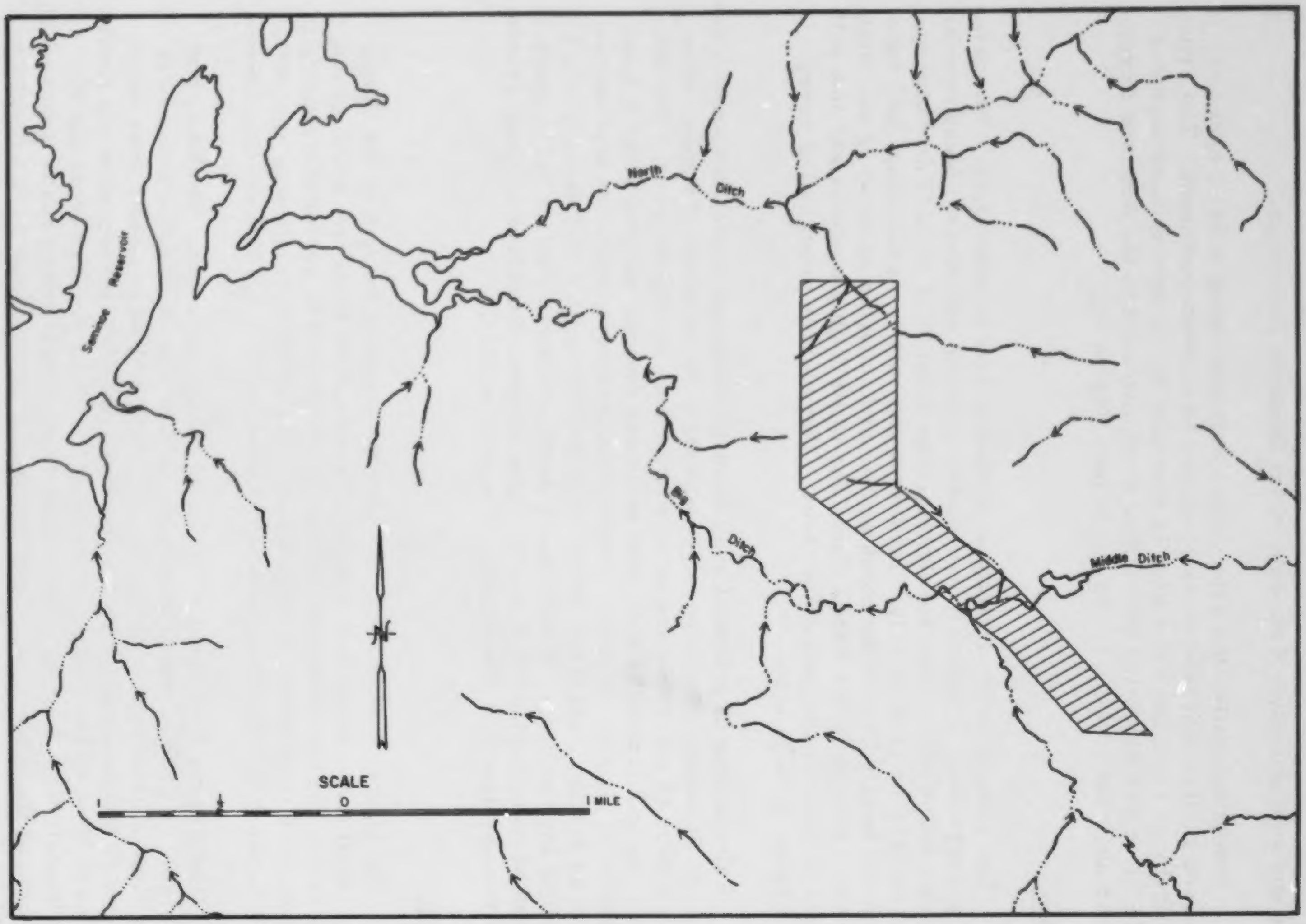

Seminoe Reservoir
North Ditch
Big Ditch
Middle Ditch
N
SCALE
1
0
1 MILE

Figure 29. Surface drainage in the vicinity of the Medicine Bow Mine, Wyoming.

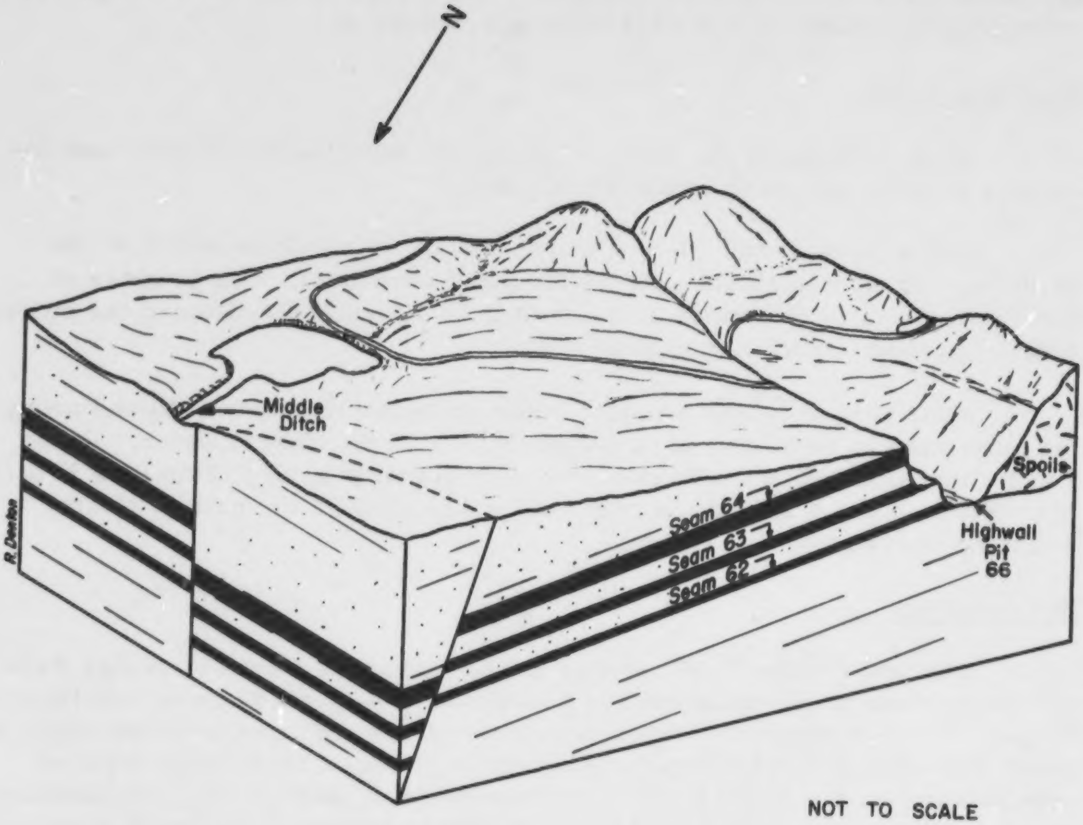

N
Middle Ditch
Seam 64
Seam 63
Seam 62
Spoils
Highwall Pit 66
R. Denton
NOT TO SCALE

Figure 30. Idealized block diagram showing major geologic features. Medicine Bow Mine, Wyoming.

faults can be seen to intersect the highwall pits, but none are considered of regional importance.

The soil in the vicinity of the mine is very sandy and extends 4 to 5 ft below the surface. Figures 31 and 32 show detailed core descriptions for Holes MBW 33-11-1 and MBW 33-4-2. The coals are numbered from oldest to youngest. Separating the coals is a sequence of fine-trained rocks grading from sandstones to shaley siltstone. Field logs of the holes completed during the investigation are presented in Appendix A.

Sampling Points

Figure 33 shows the general configuration of the mined area and locations of holes and surface sampling points.

Holes 33-4-1 and 33-4-2 were drilled on opposite sides of the fault zone which was established by the mine personnel. One purpose of these holes was to determine if the fault zone appreciably affected the movement of ground water from east to west.

Four surface water samples were collected from ponds in and around the mine area to establish any relationships with the ground water. Ponds 1 and 2 are situated to the west of the mine adjacent to Big Ditch (see Figure 33). Ponds 3 and 4 are on the east side of the mine in the path of future stripping operations.

Hydrogeology

Recharge to the Tertiary Age Hanna and to the Cretaceous Age Ferris Formations in the mine area is postulated to be from the east and from deeper, northwestward flowing waters moving upward from artesian aquifers below the coals (27). Additional recharge may result from infiltration of precipitation on the land surface, but this would be negligible. The Medicine Bow Mine lies parallel to Big Ditch, a major tributary to the North Platte River. Middle Ditch, a tributary to Big Ditch, is intersected by the mining operations. Although intermittent, it is likely that the alluvial materials beneath these streams afford some recharge to the underlying materials or, at a minimum, provide a shallow conduit for water movement to the Seminoe Reservoir. Figure 33 shows a portion of the drainage basin which represents the area of the mine sampled for this investigation. The drainage basin for Big Ditch actually extends a considerable distance to the south and to the east. The southern divide includes part of the spoils from the Seminoe Mine, and the eastern extension of the Big Ditch drainage encompasses two older, currently abandoned strip mine areas. It is doubtful that these abandoned areas would significantly affect the quality of any waters at the Medicine Bow Mine.

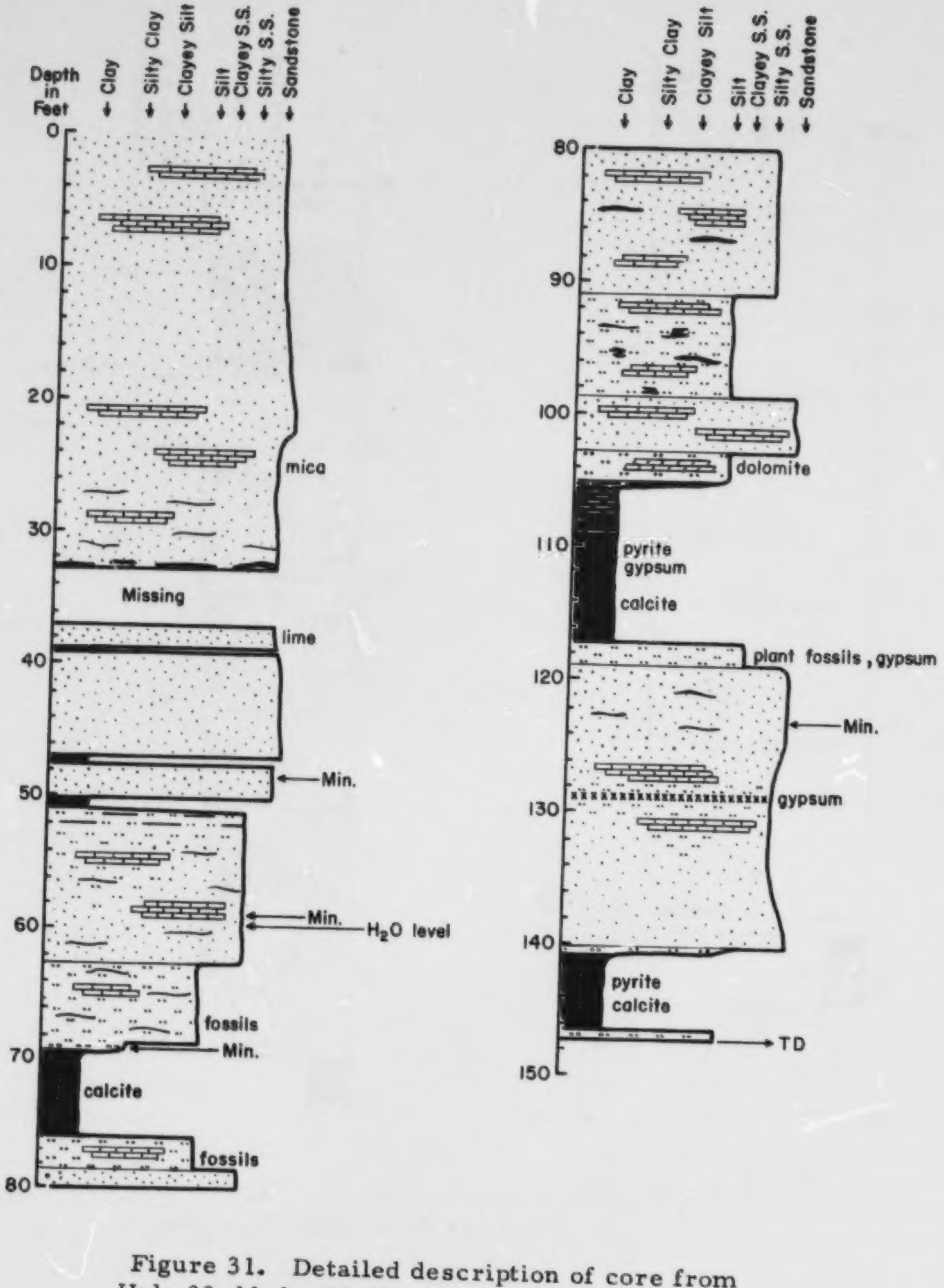

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
30
40
50
60
70
80
mica
Missing
lime
Min.
Min.
H₂O level
fossils
Min.
calcite
fossils
80
90
100
110
120
130
140
150
dolomite
pyrite
gypsum
calcite
plant fossils, gypsum
Min.
gypsum
pyrite
calcite
TD

Figure 31. Detailed description of core from Hole 33-11-1. Medicine Bow Mine, Wyoming.

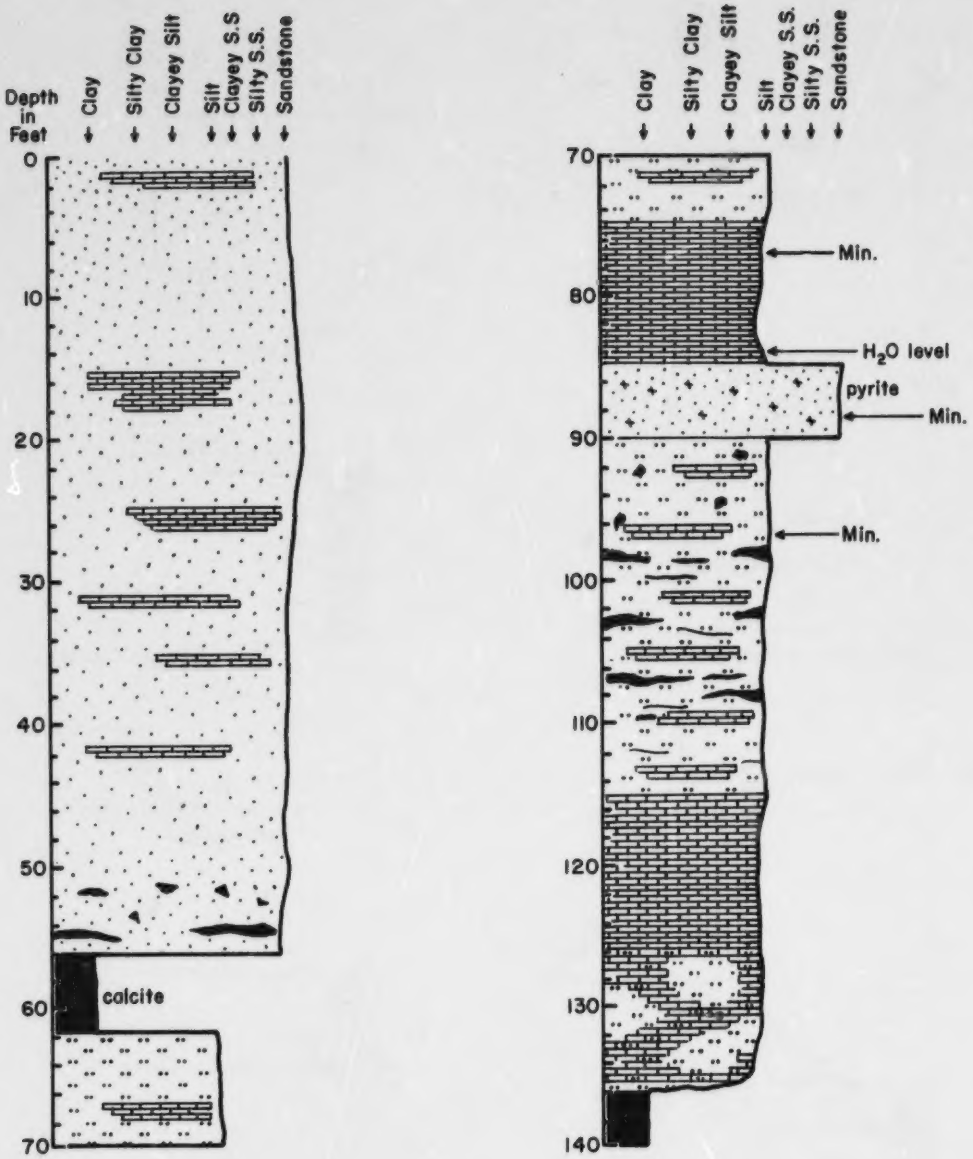
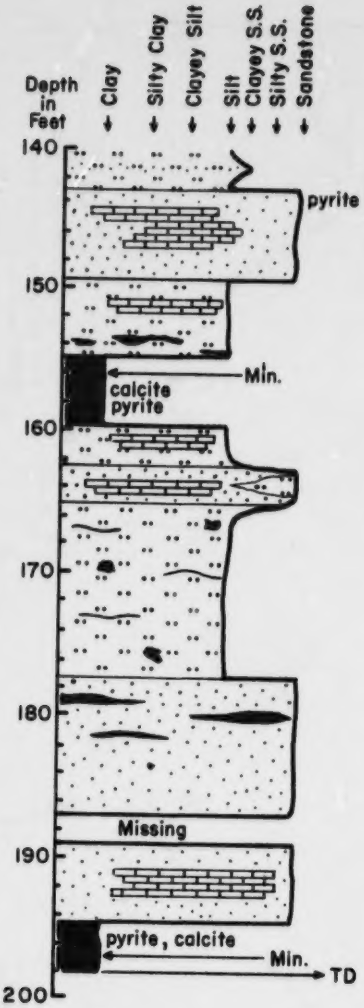

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S
Silty S.S.
Sandstone
0
10
20
30
40
50
60
70
calcite
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
70
80
90
100
110
120
130
140
Min.
H_2O level
pyrite
Min.
Min.

Figure 32. Detailed description of core from Hole 33-4-2. Medicine Bow Mine, Wyoming.



Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
140
150
160
170
180
190
200
pyrite
Min.
calcite
pyrite
Missing
pyrite, calcite
Min.
TD

Figure 32 (Cont.). Detailed description of core from Hole 33-4-2. Medicine Bow Mine, Wyoming.

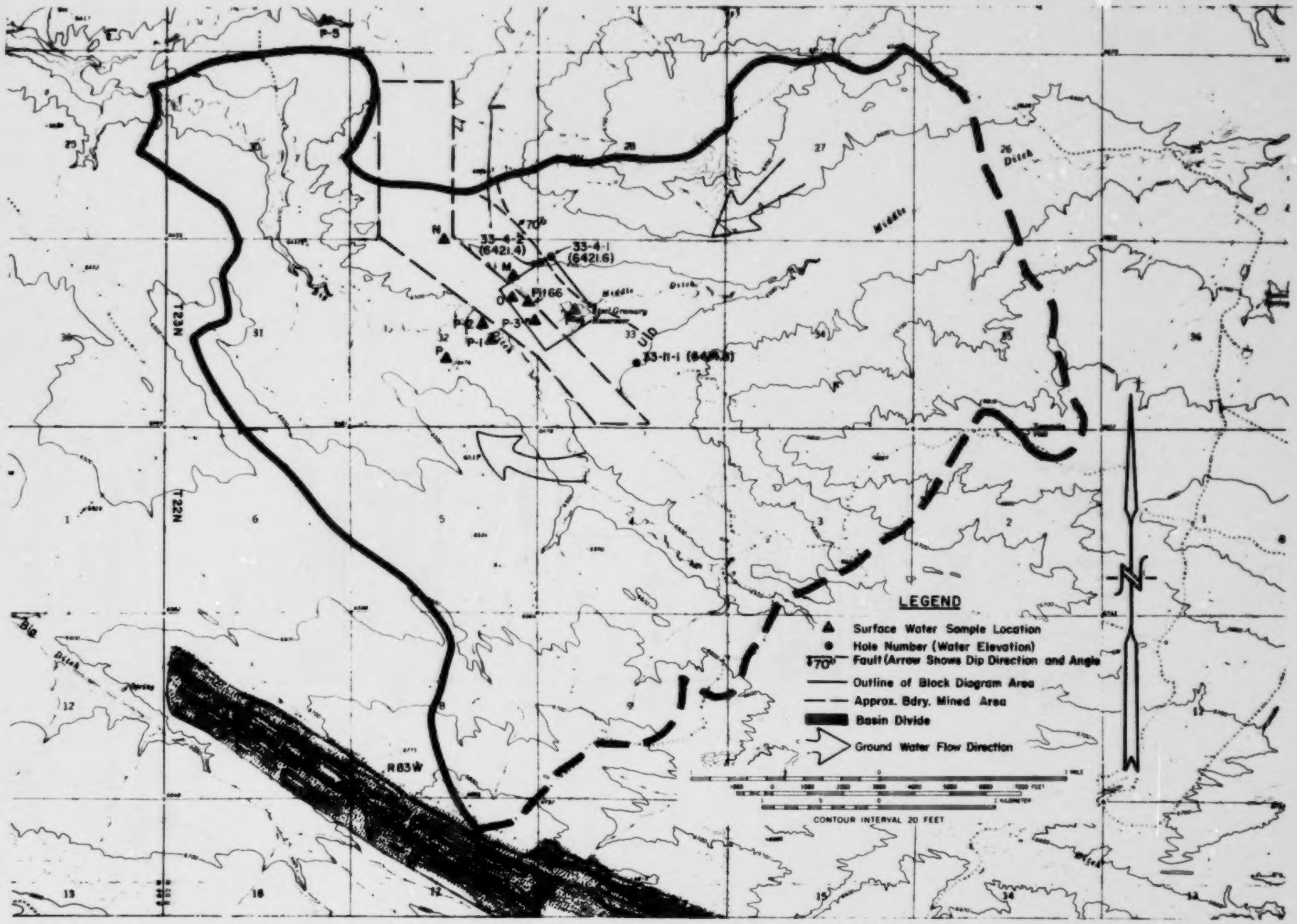

P-5
28
27
26
Ditch
Middle
N
33-4-2
(6421.4)
33-4-1
(6421.6)
M
O
P1166
P-2
P-3
P-1
P
32
Middle
Ditch
33
U
D
33-R-1
70
31
34
35
36
T23N
T22N
1
6
5
4
3
2
Big
Ditch
12
8
9
R83W
13
18
17
15
14
LEGEND
Surface Water Sample Location
Hole Number (Water Elevation)
Fault (Arrow Shows Dip Direction and Angle
Outline of Block Diagram Area
Approx. Bdry. Mined Area
Basin Divide
Ground Water Flow Direction
CONTOUR INTERVAL 20 FEET

Figure 33. Sample location map. Medicine Bow Mine, Wyoming.

Ground-water movement through the mine area appears to be west-northwest based on the work conducted by Davis (27). It should be noted, however, that this movement was based on depth-to-water data from holes of varying depths throughout the basin, and not on the basis of holes completed in a particular aquifer (27). The ground-water flow direction may well reflect the northwest trend of faults in the area as well as the surface drainage to the northwest.

Water from Pit 66 is pumped into a sump in the spoils west of the mine, from which it is further pumped into two settling ponds along Big Ditch (see Figure 33). Seepage in the west wall of the pit, below the sump, indicates that some recirculation is occurring. The water in the settling ponds is not likely to reenter the mine because of the relative position of the ponds with respect to the areal ground-water gradient.

Two holes drilled on opposite sides of the north-south trending fault in the mine area appear to substantiate some of the discussion concerning ground-water movement. Hole 33-4-1 located on the east side of the fault produced 50 gpm, whereas Hole 33-4-2 on the west side of the fault produced a maximum of 25 gpm (see Figure 33). Figure 34 shows the water production from each of these holes versus depth. The main producing zones in these two holes are the interburden materials associated with the coals. The higher water production during the drilling of Hole 33-4-1 is probably the result of higher secondary permeability from fault-related fractures, and from being in continuity with waters from the recharge area. The fault in this instance appears to be acting as a barrier to flow from the east. The water level elevation in Hole 33-11-1 also seems to indicate a gradient to the south on the west side of the fault. All three holes show water production from interburden materials.

Ground-water discharge, based on the direction of ground-water movement, would appear to be occurring to the west in the North Platte River, and locally to those areas that are wet throughout the year.

Mineralogy

A lithologic examination of core samples from Holes 33-11-1 and 33-4-2 showed the average percentage of the components in overburden to be approximately 55% sandstone, 25% siltstone, 5% limestone, and 15% coal. The sandstones were generally highly calcareous.

X-ray diffraction of selected bulk samples revealed calcite and dolomite to be the main carbonates, with siderite present in some cases (Table 10). Of the clay minerals which comprised 4% to 21% of each of the samples, kaolinite predominated, with clay-mica present in all cases but in minor amounts. Montmorillonite was present in minor-to-trace amounts in some

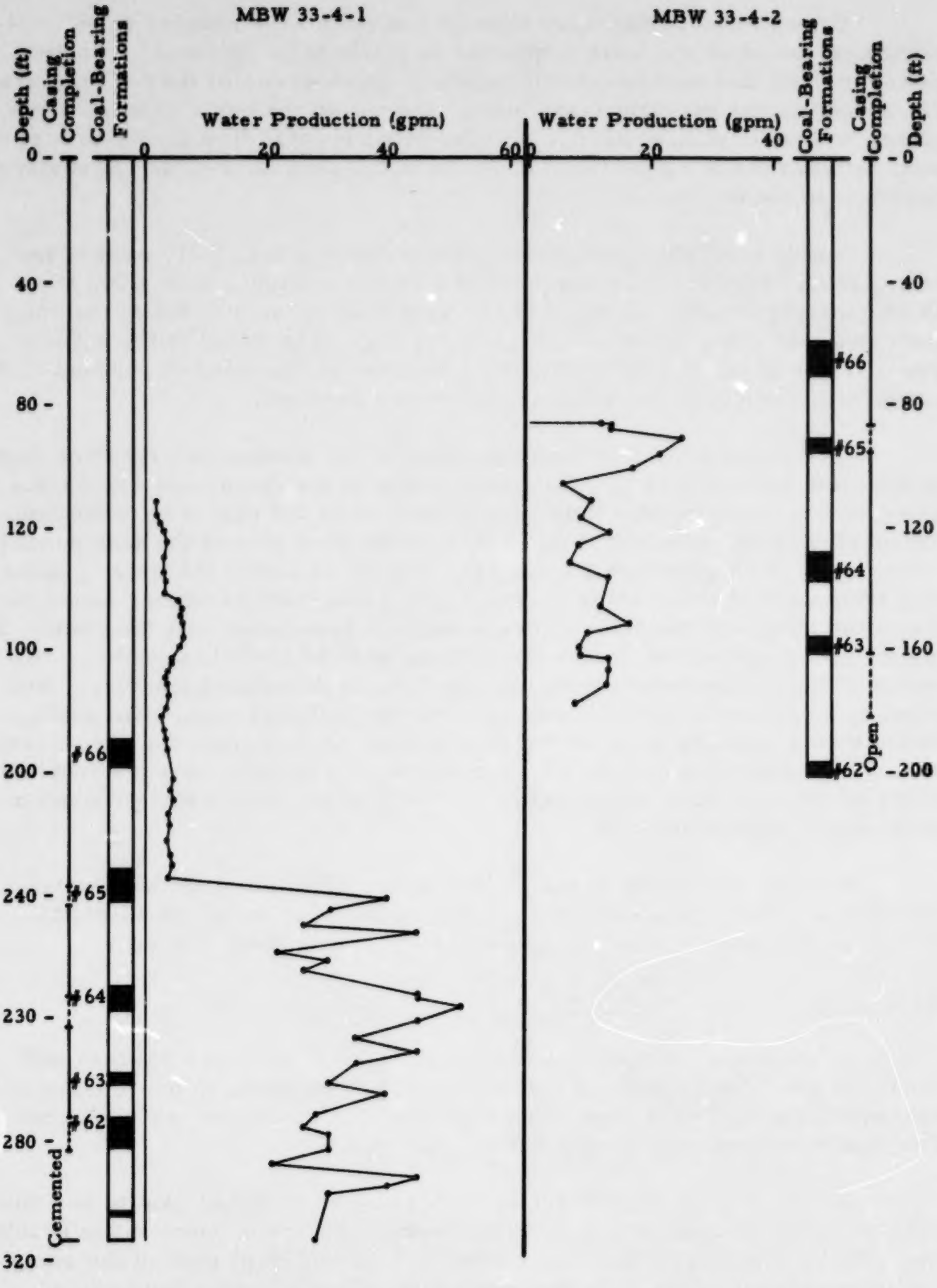


Figure 34. Water production versus depth. Medicine Bow Mine, Wyoming.

TABLE 10. X-RAY DIFFRACTION DATA MEDICINE BOW MINE, WYOMING

										Hole 33-4-2			Hole 33-11-1			Soil from Haul Road	Soil from 33-4-2	Topsoil from Stockpile East of Main Haul Road	Encrust. Between Settling Ponds
	Alkali	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 66	Lake	S3-B	75-80'	85-90'	95-100'	47.51'	59'	69'	29	31	32	34
Quartz	50	50	55	55	40	45	60	60	60	50	50	55	50	50	40	70	70	70	70
Feldspars	10	10-15	25	5	5	10	10	10	25	5-10	5	10	20	10	5	5	10	5	5-10
Kaolinite	10	10	10	5	20	10	10	10	5-10	10-15	5-10	--	15	10	10-15	5	5	5-10	5
Montmorillonite	--	--	--	5	--	5	5	5	--	Tr	--	--	Tr	--	--	Tr	--	Tr	--
Mica	5	10	--	5	10	5	10	5	Tr	5	5	10	5	5	5-10	Tr	5	Tr	5
Dolomite	--	5	5	--	5	15	3	5	Tr	10	30	5	5-10	5	Tr	--	Tr	--	--
Calcite	2	5	2	--	10	10	2	5-10	5	10	1	10	Tr	Tr	5	--	5	5	?
Siderite	--	--	--	--	--	--	--	--	--	--	--	--	--	5	--	--	Tr	--	--
Gypsum	5	--	3	15	--	--	Tr	?	--	--	--	--	Tr	--	--	--	--	--	--
Anhydrite	--	--	--	--	--	--	Tr	--	--	--	--	--	--	--	--	--	--	--	--
Pyrite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--
Thenardite	15	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arcanite	3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CLAY FRACTION (<2μ)																			
Wt % of Total	ND	11	10	4	21	15	8	9	4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Kaolinite	ND	M	M	M	M	M	M	M	M	M	M	M	M	M	M	ND	M	M	ND
Illite	ND	m	m	m	m-M	m-M	m-M	m	m	m-M	m	m	m	m	m-M	ND	m	m	ND
Montmorillonite	ND	--	--	--	Tr	m	Tr	m	Tr	m	Tr	m	m-M	--	--	ND	Tr	--	ND
Vermiculite	ND	--	Tr	--	--	--	--	--	Tr	--	--	--	--	Tr	--	ND	--	--	ND

ND -- not determined P -- predominant (est. +80%) M -- major (est. 40-80%) m -- minor (est. 10-40%) Tr -- trace (est. 1-10%)

samples. Both gypsum and pyrite were observed in x-ray diffraction patterns in addition to being observed throughout the cores.

Water Chemistry

Examination of the water data (see Table 11) revealed that both samples from Hole 33-11-1 were severely in error as indicated by the lack of cation-anion charge balance. Surface Sample S-3B is also suspect for the same reason. Ignoring these three analyses, the vector diagram (see Figure 35) for the Medicine Bow waters cluster toward the calcium-magnesium-sulfate compositional area. One exception to this is the Seminoe Reservoir sample which is a calcium-bicarbonate type water.

Inspection of drilling logs for Hole 33-4-1 showed that the casings were perforated opposite the coal beds. Ground waters were high in sulfates because the represented water from coal beds. In order to determine if ground water from beds other than coal was compositionally similar to waters from the coal, U. S. Geological Survey data of several ground and surface waters (28), both adjacent to and removed from the mine area were plotted as a vector diagram (see Figure 36). These water analyses were all compositionally similar to the waters obtained at Medicine Bow during this project. This indicates that either: a) the ground water has been mixed with surface water, or b) the ground water has independently reached the same composition as the surface water. Because the composition of ground water outside and upgradient of the mining area (Sample 33-4-1) was similar to ground-water compositions at the mine, it was concluded that the latter is the case. This is not an unreasonable conclusion given the nature of the rocks underlying and in between the coal seams in this area. Any clay beds which might act as barriers to mixing of ground-water ions are notably lacking. The ground-water compositions in this area are, therefore, a function of mixing between water types which might have occurred had communication between aquifers been restricted. As such, they represent an average composition of waters moving through coals, sandstone, and shales.

Input Parameters

The following is a summary of the important parameters from the Medicine Bow Mine that represent inputs to the development of the predictive method:

Climate. Average infiltration is minimal due to high evapotranspiration and low precipitation. Because half of the annual precipitation occurs during April, May, and June, flushing of solubles from the spoils is most likely to occur during these months or during sudden storms in the summer months.

TABLE 11. WATER DATA
MEDICINE BOW MINE, WYOMING

Samples	Pit 1	Pit 2	Pit 2A (repeat)	Pit 3	Pit 4	Pit 5	Pit 66	S3-B	Lake (Seminoe Reservoir)	Water Truck	Well 33-4-1	33-4-9 (repeat)	Well 3-11-1	Well 33-11-1 (repeat)
Field Measurements														
Temperature (°C)	10.5	6.5	15.0	7.0	14.5	9.5	14.0	6.5	15.0	5.0	10.0	11.0	14.0	13.5
pH	6.0	6.0	7.9	6.0	6.5	5.0	7.2	6.0	7.8	6.5	6.5	8.2	11.0	60
Dissolved O_2 (mg/l)	2	5	9	4	8	8	6	4	5	6	3	4	7	6
H_2S (mg/l)	0	0	0.1	0.1	0	0.1	0.1	0	0.1	0	0.1	0.1	0	0.1
Conductivity (μmhos)	3,625	4,125	6,000	3,950	2,500	2,375	6,000	6,000	4.25	1,675	2,400	3,900	3,950	5,537.5
Laboratory Measurements														
Temperature (°C)	10.5	6.5	15.0	7.0	14.5	9.5	14.0	6.5	15.0	5.0	10.0	11.0	14.0	13.5
pH	6.0	6.0	7.9	6.0	6.5	5.0	7.2	6.0	7.8	6.5	6.5	8.2	11.0	12.0
Total Dissolved Solids (mg/l)	5,864	6,614	5,662	6,544	2,962	1,760	8,430	10,419	162	2,889	3,270	3,840	3,078	2,342
Ca^{+2} (mg/l)	381	445	431	515	262	215	559	400	31.8	222	335	365	736	582
Mg^{+2} (mg/l)	390	484	450	497	193	193	621	808	10.2	174	252	257	<1	<0.2
Na^{+1} (mg/l)	460	576	515	521	234	95	812	1,150	19.9	215	165	318	178	189
K^{+1} (mg/l)	10.7	13.2	14.2	11.2	10.0	8.3	15.8	13.7	2.0	8.6	7.2	13.8	45.0	110.0
$F\dot{e}$ (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	0.7	<0.1	<0.1	<0.1
SO_4^{-2} (mg/l)	3,190	3,950	3,516	3,880	1,760	1,070	5,118	8,360	70	1,560	1,905	2,350	1,430	760
HCO_3^{-1} (mg/l)	410	180	390	675	290	189	668	650	113	250	598	309	0	0
CO_3^{-2} (mg/l)	0	30	0	0	0	0	0	0	0	0	0	0	60	90
Cl^{-1} (mg/l)	46.0	61.0	100.0	66.0	35.0	27.0	137.4	70.0	22.0	40.0	37.2	52.5	30.0	33.7

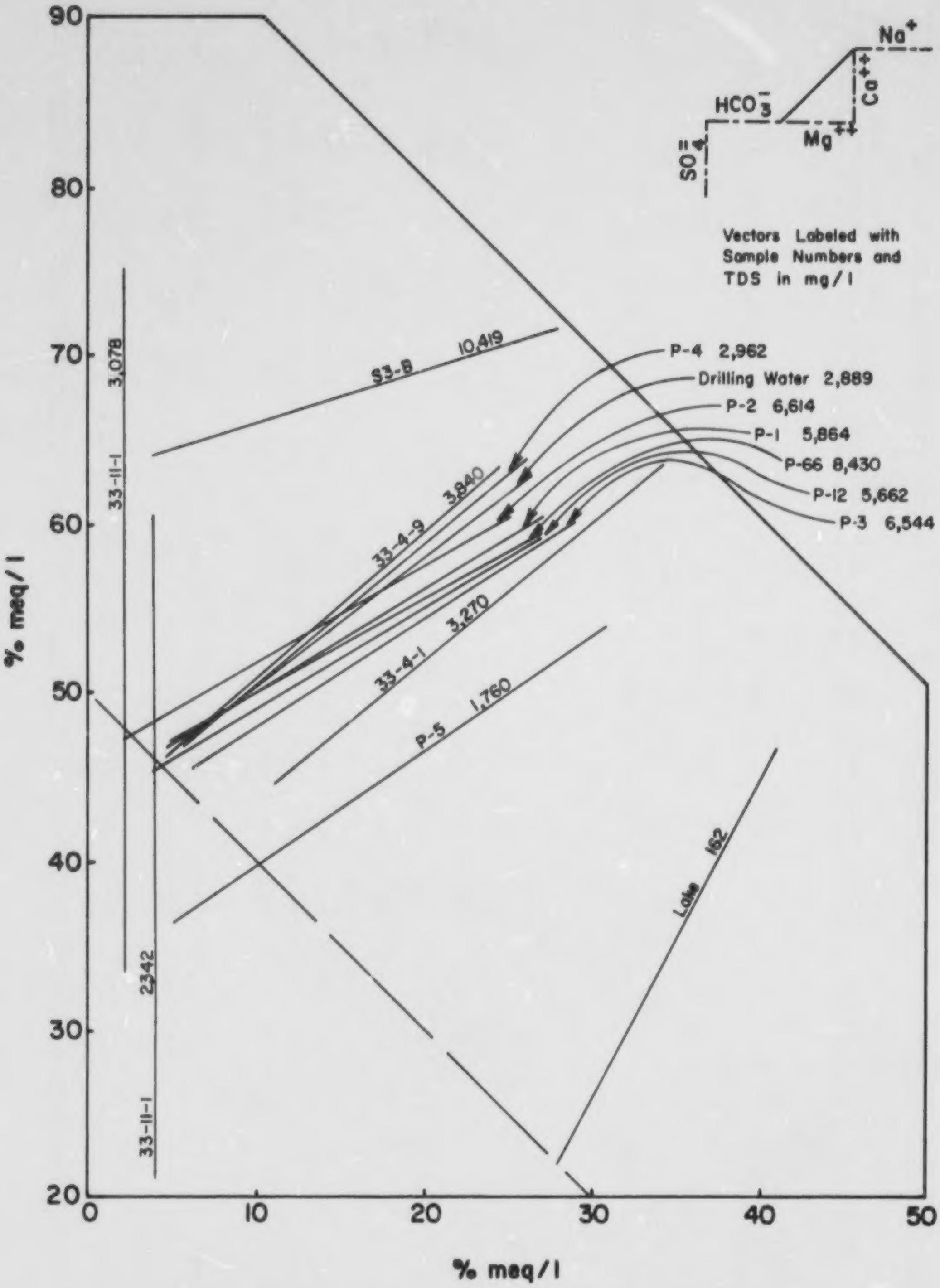


Figure 35. "Vector" diagram of water compositions. Medicine Bow Mine, Wyoming.

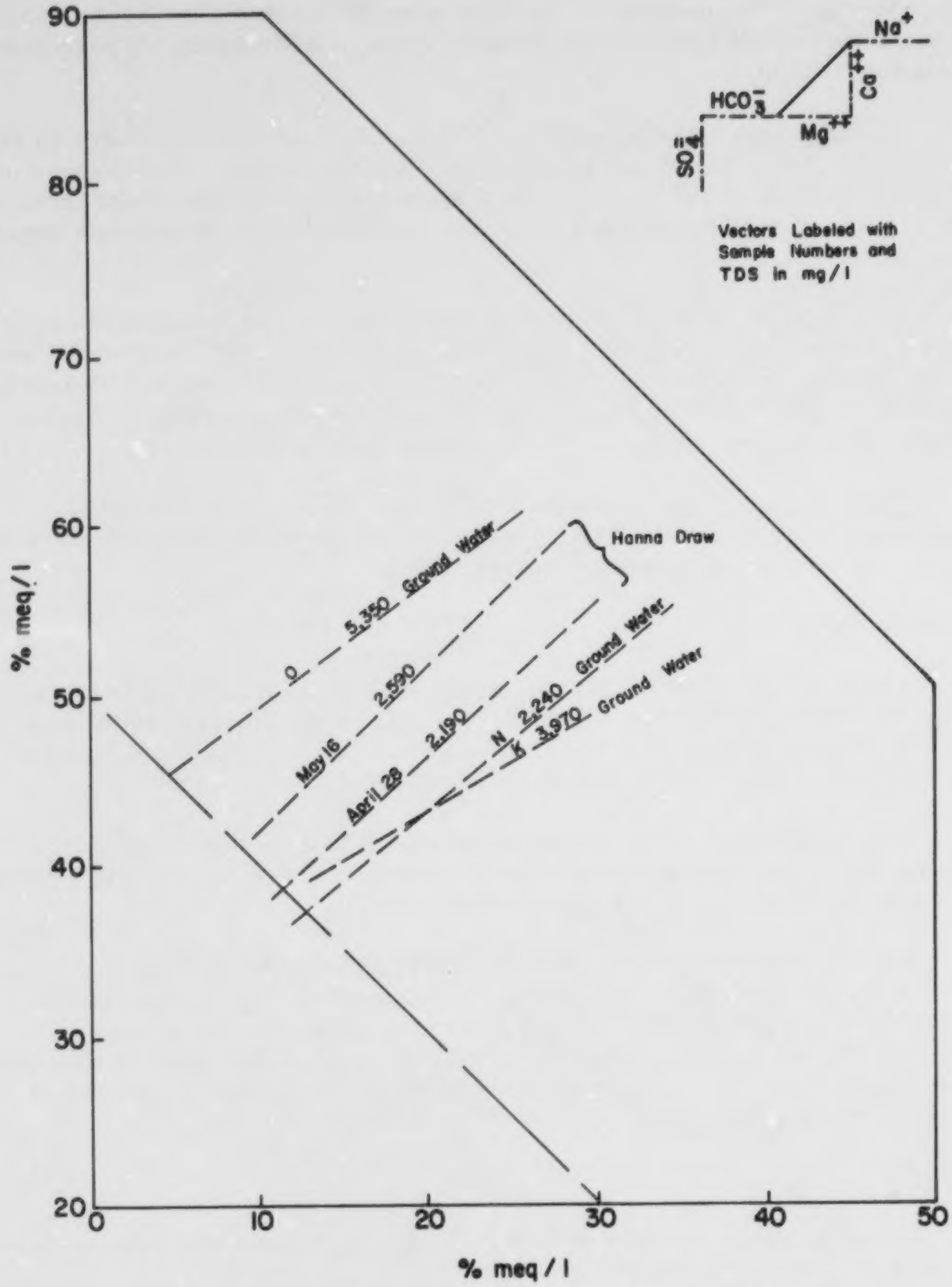


Figure 36. "Vector" diagrams of water compositions. Medicine Bow Mine, Wyoming. (Dashed lines from U. S. G. S. Water Resources Data for Wyoming, 1975: Platte River Basin and Ground Water in Wyoming. Analyses appear in Appendix Table C-10.).

Geology. The geology of the mine area is structurally simple, involving nearly horizontal beds of sedimentary rock. Lenticularity of beds makes correlation difficult.

Hydrogeology. Water-production logs show that ground water in the Medicine Bow Mine area is in an unconfined configuration. The absence of impermeable clays in the section would allow free mixing of waters from sands, coals, silts, and fractured shales, thus producing an average water composition.

Mineralogy. Potentially reactive minerals in the rocks of the overburden include calcite, dolomite, gypsum, pyrite, kaolinite, and at the surface, thenardite and arcanite. The latter two are secondary, and reflect the high sulfate content of evaporating surface waters. The amount of carbonates present in the overburden exceeds the amount of pyrite.

Water Chemistry. Ground and surface waters alike are of the calcium-magnesium-sulfate type. One exception is the Seminoe Reservoir sample, which is a calcium-bicarbonate water.

ROSEBUD MINE

The Rosebud Mine is located approximately 3 mi north of the town of Hanna, Wyoming, in T22 and 23N, R81W. It is approximately 15 mi east of the Medicine Bow Mine. The Rosebud Mine is owned by the Rosebud Coal Sales Co. and is operated by Peter Kiewit and Sons Co.

The topography in the Rosebud Mine area is similar to that of the Medicine Bow Mine. Major recent strip-mining activity has been in a northwest trend, with mining occurring to the northeast.

No major drainages occur in the Rosebud Mine area; however, intermittent streams to the east of the Rosebud Mine area are draining to the east-northeast, whereas those to the west are draining to the south-southwest. Surface drainage in the vicinity of the Rosebud Mine is shown in Figure 37. Considerable ponding exists in the older Nugget strip area in Section 10 to the south of currently active operations.

Climate

Climate conditions do not differ appreciably from the Medicine Bow Mine (see Medicine Bow Mine).

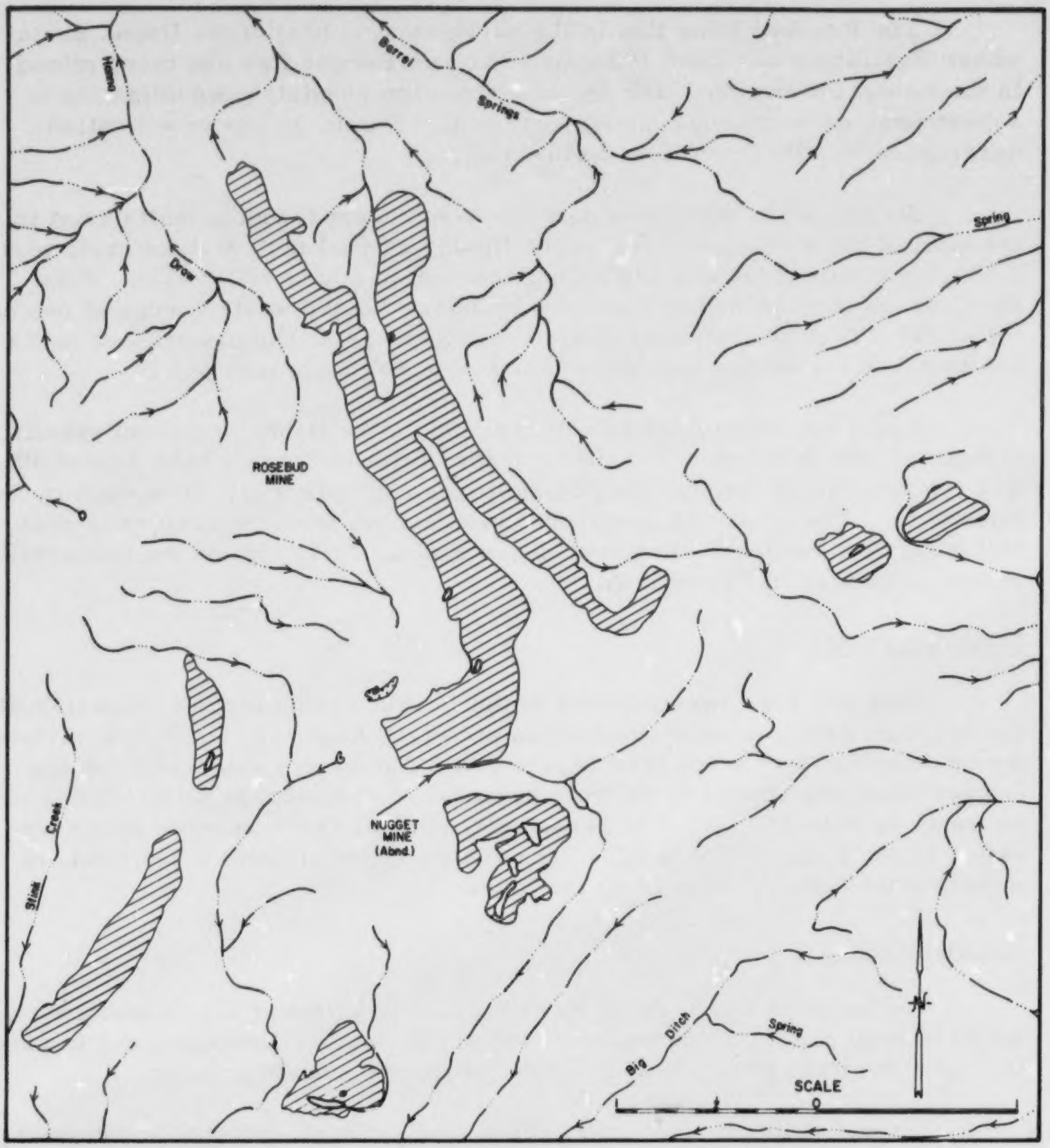

Hanna
Draw
Barrel
Springs
Spring
ROSEBUD MINE
NUGGET MINE (Abnd)
Stink
Creek
Big
Ditch
Spring
SCALE
0
N

Figure 37. Surface drainage in the vicinity of the Rosebud Mine, Wyoming.

Geology

The Rosebud Mine lies in the south-central part of the Hanna Basin where Tertiary coals from Paleocene through Eocene Age are being mined in the Hanna Formation. The Hanna Formation consists predominately of sandstones, carbonaceous shales, and coal. Figure 38 shows a detailed description of core from Hole 3R4S-15-1.

Structurally, numerous northwest-southeast trending faults exist in the area to the southwest. A steeply dipping normal fault strikes northwest through the mine area and has a displacement of 600 to 800 ft (29). This fault passes through and serves as a boundary for the western edge of one of the active pits at the Rosebud Mine (see Figure 39). The majority of faults southwest of the mine show displacements of not more than 200 ft.

Coals are being mined from Seam 80 on the flanks of a local synclinal structure, which accounts for the L-shaped form of the pits (see Figure 40). The subbituminous coal of Seam 80 averages approximately 15-ft thick in the mine area. The overlying sandstone units contain scattered traces of coal with alternate stringers of carbonaceous shale. Field logs of the holes drilled are presented in Appendix A.

Sampling Points

Only two holes were drilled at the Rosebud Mine for the collection of ground-water samples and overburden material; however, numerous surface water samples were taken (see Figure 39). The waters sampled from the Nugget Mine pits appear to be from ground-water discharge in that the depth-to-water in Hole 3R4S-15-1 is perennially similar to the surface water elevation in the Nugget Mine ponds. The quality of water from these ponds is significantly different than from the holes.

Hydrogeology

Recharge in the Rosebud Mine area occurs principally from direct infiltration of precipitation on the sands of the Hanna Formation, and in part through downward percolation along the northwest trending faults.

Ground-water movement is not as well defined, but can be assumed to follow the direction of the surface drainage which is south-southwest. Water level elevations in Holes 34R4-16-1 and 3R4S-15-1 reflect this southerly movement (see Figure 39).

Ground-water discharge in the mine area is occurring to some extent in the abandoned Nugget Mine pits. Movement in this direction may be caused in part by the fault which serves as a boundary to the mine operations

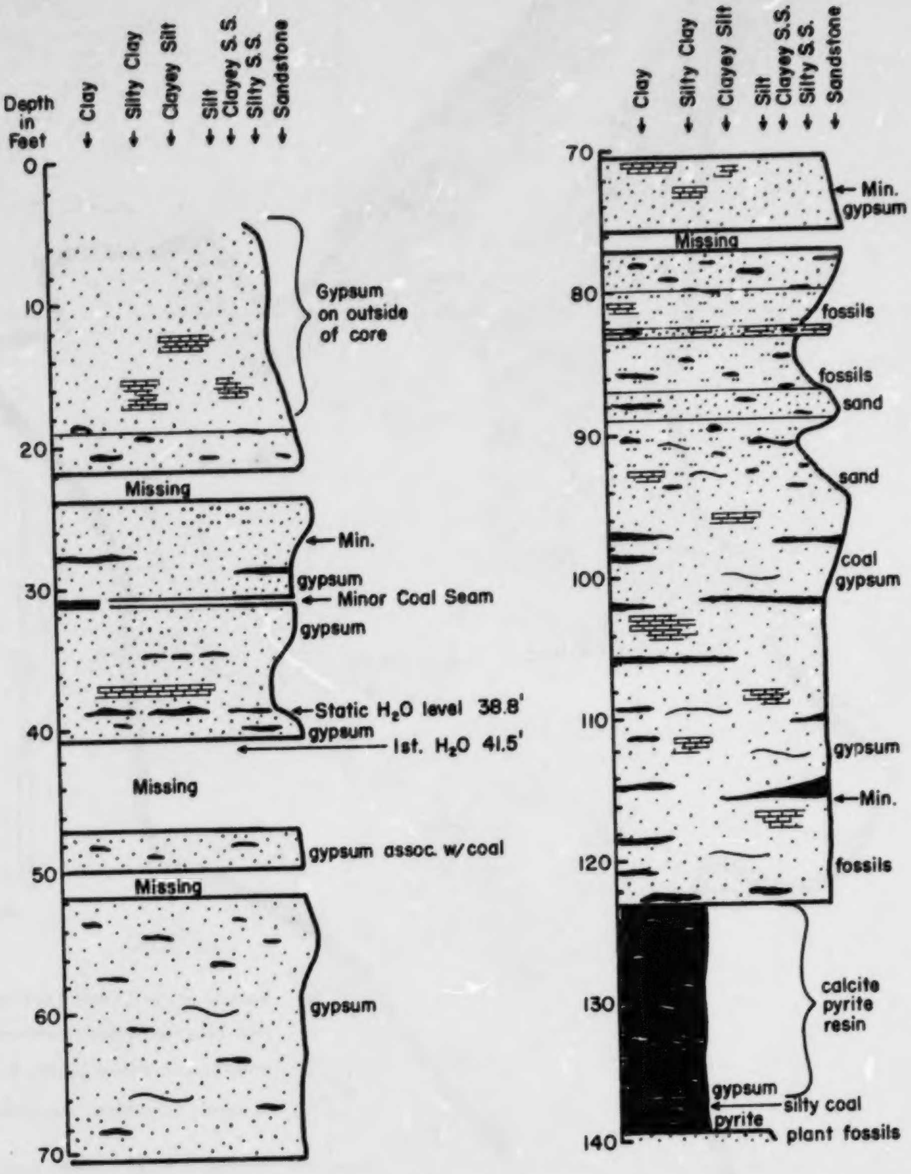

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
30
40
50
60
70
Gypsum on outside of core
Missing
Min.
gypsum
Minor Coal Seam
gypsum
Static H₂O level 38.8'
gypsum
1st. H₂O 41.5'
Missing
gypsum assoc. w/coal
Missing
gypsum
70
80
90
100
110
120
130
140
Min. gypsum
Missing
fossils
fossils
sand
sand
coal gypsum
gypsum
Min.
fossils
calcite pyrite resin
gypsum
silty coal
pyrite
plant fossils

Figure 38. Detailed description of core from Hole 3R4S-15-1. Rosebud Mine, Wyoming.

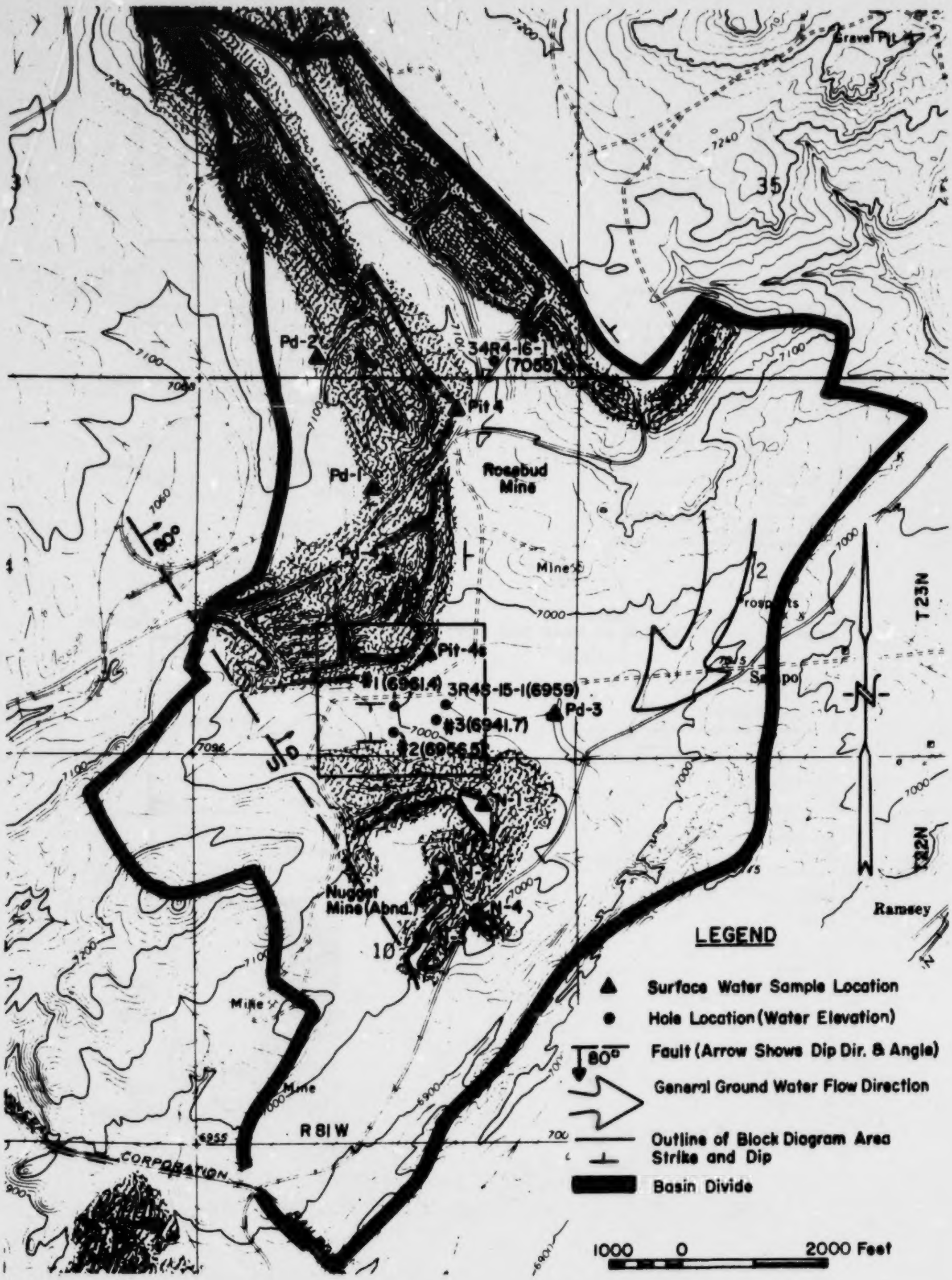

Gravel Pit
7240
35
7200
7100
7060
Pd-2
34R4-16-1
(7055)
Pit 4
Rosebud Mine
Pd-1
80°
Mine
7000
2
Prospects
Pit-4s
#1(6961.4)
3R48-15-1(6959)
#3(6941.7)
Pd-3
#2(6956.5)
7096
N-1
Nugget Mine (Abnd.)
N-4
10
Mine
Mine
6900
R 81 W
6955
CORPORATION
T23N
T22N
N
Ramsey
LEGEND
Surface Water Sample Location
Hole Location (Water Elevation)
80°
Fault (Arrow Shows Dip Dir. & Angle)
General Ground Water Flow Direction
Outline of Block Diagram Area
Strike and Dip
Basin Divide
1000
0
2000 Feet

Figure 39. Sample location map. Rosebud Mine, Wyoming.

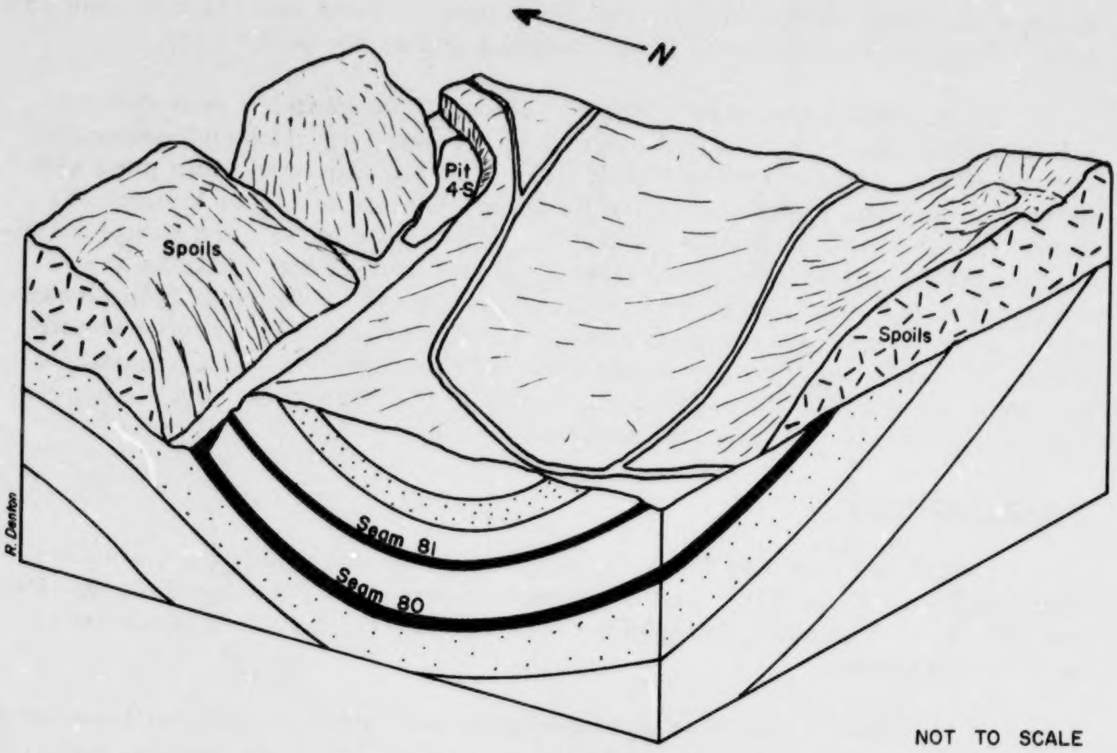

N
Pit 4-S
Spoils
Spoils
Seam 81
Seam 80
R. Denton
NOT TO SCALE

Figure 40. Idealized block diagram showing major geologic features. Rosebud Mine, Wyoming.

and in part by the synclinal structure on which the pits are developed. Hole 3R-RS-15-1 produced considerably more water than Hole 34R4-16-1, which is probably a result of its closer proximity to the axis of this synclinal feature. Figure 41 shows water production versus depth for Hole 3R4S-15-1.

Mineralogy

Lithologic examination of Core 3R43-15-1 showed it to be composed of approximately 75% sandstone and 10% siltstone (both calcareous), and 15% coal. Gypsum was observed in the clastics and pyrite in the coal.

X-ray diffractometer scans of selected bulk samples revealed calcite and dolomite to be present in most of the samples, although generally occurring in small quantities (Table 12). The clay fraction from pond sediment samples and from some core samples consists of major amounts of kaolinite and minor amounts of clay-mica, whereas other core samples contain major quantities of montmorillonite in addition to the kaolinite and clay-mica. Clay-size quartz is present, but in minor amounts in most samples. In some cases, however, clay-size calcite becomes a major constituent. X-ray diffractometer scans also revealed gypsum to be present in one core sample as well as in the majority of samples from surface ponds. Pyrite was detected in the coal sample.

Water Chemistry

All water samples from the Rosebud Mine were plotted as a vector diagram (see Figure 42). Cation-anion imbalance for Samples R-1, R4-P4, and 3R-45-15-2 is sufficiently large to disqualify them from consideration as valid data points.

Essentially all the samples analyzed have similar compositions, with the exception that the calcium-magnesium ratios divide the samples into two groups (Table 13). One group contains surface waters from the Nugget Mine, which are enriched in magnesium relative to calcium, with a high TDS value. The second group contains both surface and ground waters with calcium/magnesium ratios similar to those ratios for other mines.

The enrichment in magnesium over calcium found in the Nugget Mine waters is a function of the relative solubilities of magnesium and calcium sulfate. In all cases, the concentration of aqueous magnesium sulfate is ten to one hundred times higher in the Nugget Mine waters than in the Rosebud Mine waters. While the solubility of gypsum in these waters has been exceeded at this point in time, the solubility of starkeyite has not. Therefore, selective removal of calcium by the precipitation of gypsum is greatly enriching these waters in magnesium.

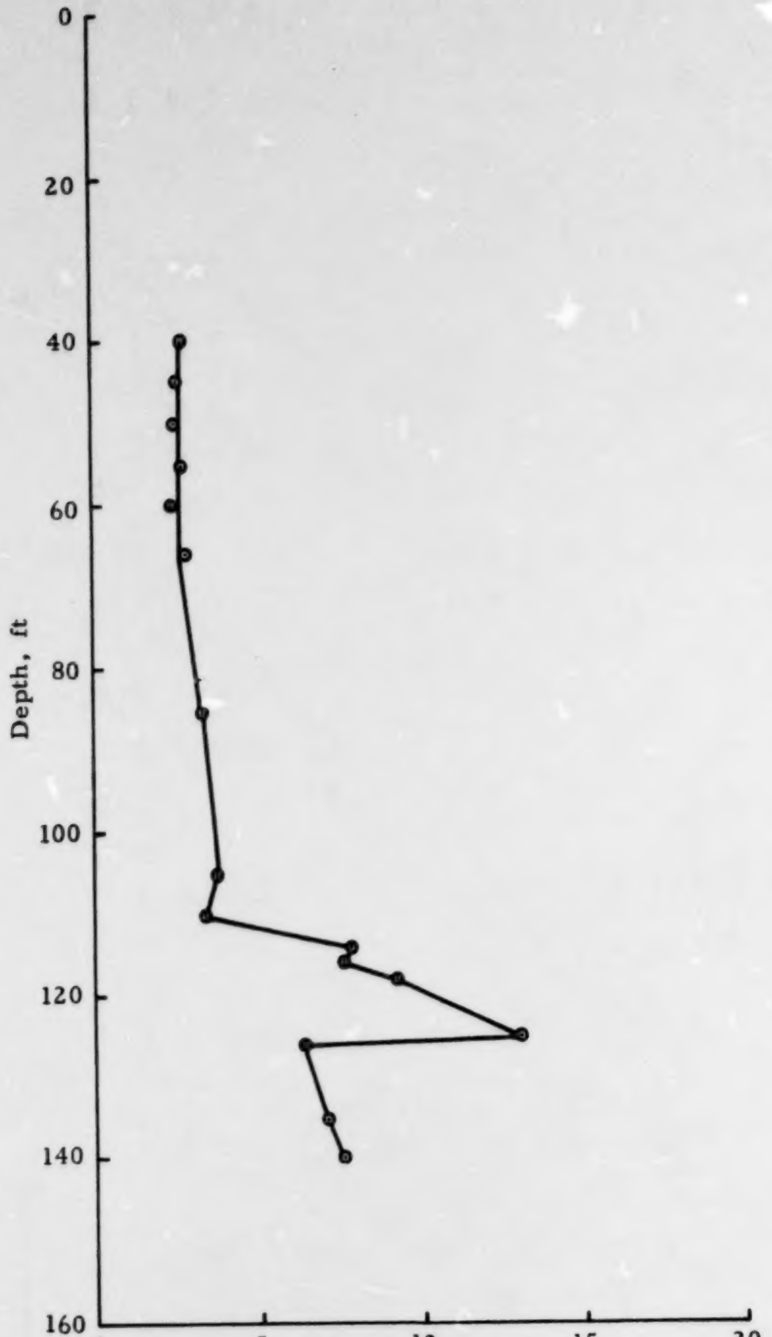


Figure 41. Water production versus depth during drilling. Rosebud Mine, Wyoming.

TABLE 12. X-RAY DIFFRACTION DATA
ROSEBUD MINE, WYOMING

	Hole 34R4-16-1			Coal	Hole 3R4S-15-1			Haul Road	Pit 4-S	Nugget									
	5 -10'	80 -85'	125 -130'	150 -155'	27'	73'	115. 9'	Soil	Soil	N1	N2	N3	N4	Pit 4	Pit 4S	Pond 1	Pond 4	Well 1	Well 2
Quartz	50	50	50	x	50	50	50	60	60	50	55	65	55	60	60	65	60	60	50
Feldspars	5-10	15-20	Tr	--	25	25-30	5-10	5-10	10	5	10	10	15	10	10-15	10	10	20	20
Kaolin	10	10	15-20	x	10	10-15	20	5	10-15	5	15	15	10	10	10	5	15	10-15	10
Montmorillonite	--	--	--	--	5	10	Tr	--	--	--	--	--	--	--	--	--	--	--	10
Mica	Tr	5	10	x	Tr	Tr	5	5-10	--	5	10-15	5	5	Tr	5	5	--	5	Tr
Dolomite	--	--	--	--	--	--	5-10	--	--	--	--	--	5	Tr	--	?	--	--	--
Calcite	5	--	--	x	Tr	Tr	Tr	--	Tr	--	--	--	--	--	?	--	?	5	5
Gypsum	20	--	--	--	--	--	--	--	--	20	5	Tr	Tr	--	--	--	--	--	Tr
Pyrite	--	--	--	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

CLAY FRACTION
(<2 μ)

	5 -10'	80 -85'	125 -130'	150 -155'	27'	73'	115. 9'	Soil	Soil	N1	N2	N3	N4	Pit 4	Pit 4S	Pond 1	Pond 4	Well 1	Well 2
Wt % Total	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	9	8	4	5	5	5	5	ND	ND
Kaolinite	M	M	M	ND	M	M	M	ND	ND	m	M	M	m	M	M	M	M	ND	ND
Illite	Tr	m	m	ND	Tr	Tr	M	ND	ND	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	ND	ND
Montmorillonite	--	--	--	ND	m	M	m	ND	ND	Tr	Tr	--	Tr	--	Tr	--	--	ND	ND
Vermiculite	--	--	--	ND	Tr	Tr	Tr	ND	ND	--	--	Tr	--	--	Tr	--	--	ND	ND

x -- present in unspecified amount

ND -- not determined P -- predominant (est. +80%) M -- major (est. 40-80%) m -- minor (est. 10-40%) Tr -- trace (est. 1-10%)

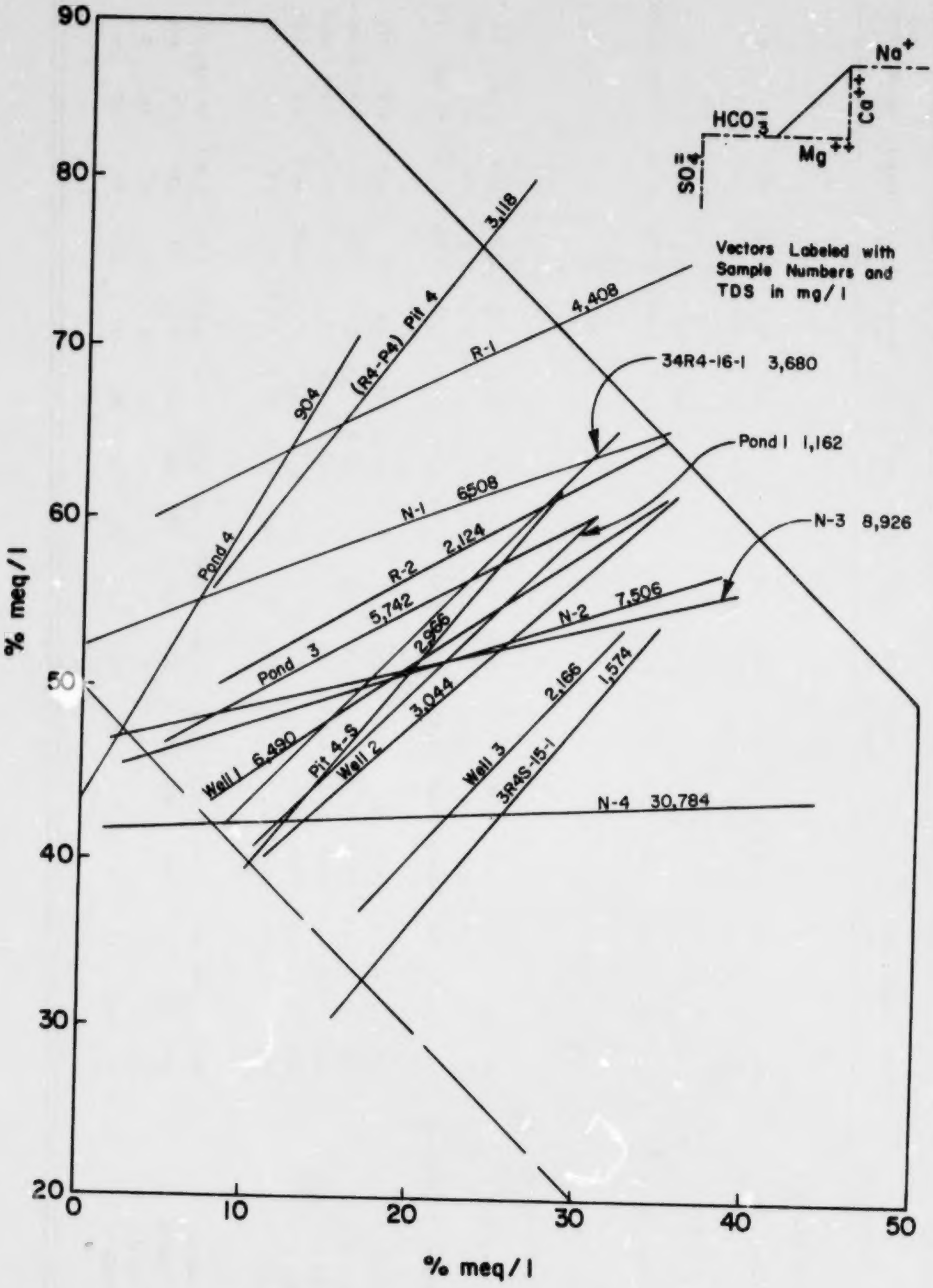


Figure 42. "Vector" diagram of water compositions. Rosebud Mine, Wyoming.

TABLE 13. WATER DATA
ROSEBUD MINE, WYOMING

Samples	Pond 1	Pond 3	Pond 4	R-1	R-2	Pit 4 (R4-P4)	Pit 4S	Well 1	Well 2	Well 3	Well 34R4-16-1	Nugget N1	Nugget N2	Nugget N3	Nugget N4	Well 3R4S-15-1
Field Measurements																
Temperature (°C)	18.5	0	14.0	12.0	11.0	12.0	14.0	11.4	10.0	9.0	11.0	15.0	13.0	15.0	12.0	0
pH	7.1	0	7.6	7.1	7.9	8.1	7.9	7.0	6.9	6.9	7.2	3.55	7.9	7.9	8.5	7.1
Dissolved O_2 (mg/l)	7	0	6	5	7	4	21	28	2	2	4	6	5	5	205	3
H_2S (mg/l)	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	<0.1
Conductivity (μmhos)	1,200	0	800	2,650	1,525	4,950	2,275	3,565	2,000	1,600	2,300	4,525	5,750	6,000	16,500	1,700
Laboratory Measurements																
Temperature (°C)	18.5	0	14.0	12.0	11.0	12.0	14.0	11.4	10.0	9.0	11.0	15.0	13.0	15.0	12.0	3.0
pH	7.1	0	7.6	7.1	7.9	8.1	7.9	7.0	6.9	6.9	7.2	3.55	7.9	7.9	8.5	7.1
Total Dissolved Solids (mg/l)	1,162	5,739	904	4,408	2,125	3,118	2,966	6,490	3,044	2,166	3,680	6,508	7,506	8,926	30,784	1,185
Ca^{+2} (mg/l)	119.5	403	124	277	145	349	354	609	345	208	481	468	522	481	411	258
Mg^{+2} (mg/l)	73.5	447.0	45.0	342.0	157.0	163.0	176.0	550.0	231.0	113.0	283.0	751.0	970.0	1,170.0	4,870.0	126.0
Na^{+1} (mg/l)	70.5	373.0	31.2	60.0	95.0	111.0	183.0	163.0	89.0	235.0	73.0	73.0	128.0	202.0	1,100.0	90.2
K^{+1} (mg/l)	9.75	16.0	5.8	13.2	9.0	10.8	10.1	9.0	8.0	9.3	13.3	19.1	38.2	34.5	6.0	6.42
Fe^{*} (mg/l)	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	0.1	<0.1	<0.2	<0.1	9.3	<0.1	<0.1	0.2	1.8
SO_4^{-2} (mg/l)	588	3,306	472	2,584	1,173	1,921	1,529	3,465	1,546	1,059	2,043	4,495	4,885	5,844	18,854	803
HCO_3^{-1} (mg/l)	194	455	0	236	244	342	506	805	549	622	543	0	351	339	623	516
CO_3^{-2} (mg/l)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	136	0
Cl^{-1} (mg/l)	23	64	17	23	25	23	33	65	29	19	19	38	73	95	555	9

Pond R4-N1 has a pH of 3.5 and is abnormally high in trace-element content. Possible causes for this are:

- Locally high concentrations in the surrounding spoils of coal, presumably pyritic, the oxidation of which would produce acid waters in the absence of carbonates.
- The dumping of effluent from an unidentified source. This could take the form of actual dumping of solid or liquid wastes into the pond, or result from introducing material hydrologically upgradient of the pit which then could alter the nature of ground water entering the pit.

Although the pH of this water was evidently correct, as supported by the trace element content, it was not possible to determine if the low pH was caused by mining conditions or by some unknown external factor. The disparity between the pH values of Pit N-1 and the three adjacent Pits N-2, N-3, and N-4 tends to suggest the second possibility.

By arranging all waters in order of increasing ionic strength, the Nugget Mine waters are distinguishable as a group, characterized by high ionic strengths (see Appendix Tables D-56 through D-59). Ground and surface waters, however, are not distinguishable on the basis of ionic strengths. Ground-water samples taken near or at a coal bed did not consistently have higher or lower ionic strengths than samples from non-coal strata. These results are similar to those from the Medicine Bow Mine and, with the exception of the Nugget Mine waters, the overall composition, ion ratios, and ionic strengths of waters from both mines are very similar.

Input Parameters

The following is a summary of the important parameters from the Rosebud Mine that represent inputs to the development of the predictive method:

Climate. Average infiltration is minimal due to high evapotranspiration and low precipitation. Flushing of solubles from the spoils is most likely to occur during April, May, and June.

Geology. The geology of the Rosebud Mine area is structurally simple. Strata are gently folded and only one fault crosses the mine area.

Hydrogeology. Ground water is unconfined as in the case of the Medicine Bow Mine area. The overburden lacks clays or shales which might allow differentiation of waters to occur. The water chemistry, therefore, reflects the composition of the entire overburden.

Mineralogy. Potentially reactive minerals in the overburden include minor amounts of calcite, dolomite, gypsum, pyrite, and kaolinite. The amount of carbonates in the overburden exceeds the amount of pyrite.

Water Chemistry. With the exception of the Nugget Mine waters, ground and surface waters at the Rosebud mine were calcium-predominant, calcium-magnesium-sulfate waters. Nugget Mine pit waters were also calcium-magnesium-sulfate waters, but magnesium was greatly enriched over calcium. No sodium-bicarbonate waters were found at this site.

KEMMERER MINE

The Kemmerer Mine is located near the towns of Frontier and Kemmerer, Wyoming, in T21N, R61W. This area is within the Kemmerer coal field which is a part of the Hams Fork coal region of western Wyoming. The Kemmerer operation involves a total of 13 coal seams. For the purposes of this report, operations on all 13 seams and the 2 tipples will be referred to collectively as the Kemmerer Mine.

Elongate ridges and valleys reflect the underlying structural geology of the area which consists of a series of north-south thrust faults. Relief in the area is approximately 600 ft. Drainage is to the east through numerous intermittent streams and ultimately south to the Hams Fork River. Surface drainage in the Kemmerer Mine vicinity is shown in Figure 43.

Climate

The Kemmerer area is semi-arid to arid, with an average annual precipitation of only 9.2 in. Winds are generally high, averaging from 12 to 14 mph. May and June produce the greatest monthly rainfall amounts, and average 1.7 in./mo. Evapotranspiration exceeds precipitation throughout the year, leaving a soil moisture deficit of 15.6 in.

Geology

The Kemmerer Mine area differs considerably from the other coal areas in the Rocky Mountains in that it lies in the Wyoming Overthrust Belt, as opposed to a basin-type structure. This belt is characterized by tightly folded Paleozoic and Mesozoic rocks which were thrust eastward over folded Cretaceous rocks during Laramide time. Younger, Cretaceous and Tertiary rocks were later deposited unconformably over the folded and faulted older rocks and are relatively flat-lying (6). The belt extends in a narrow band from the southwestern corner of Wyoming northward to the Gros Ventre uplift near Jackson Hole.

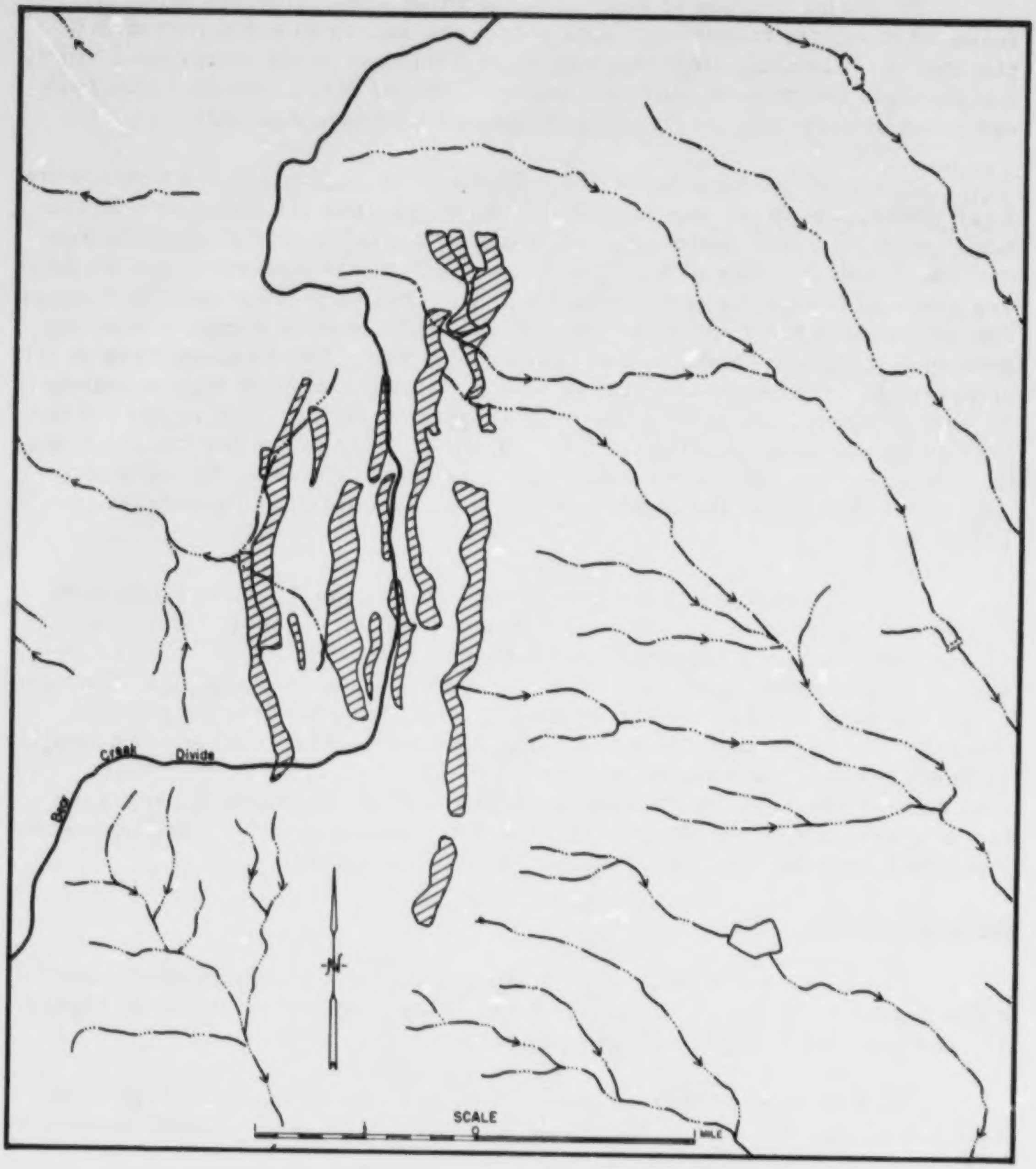

Bear Creek Divide
N
SCALE
0
MILE

Figure 43. Surface drainage in the vicinity of the Kemmerer Mine, Wyoming

No major faulting is evident in the mine area, although highwall faces often expose minor fault sets with a few inches to a few feet of displacement. The mine lies approximately 3 mi east of the Absaroka Thrust, a high-angle overthrust fault with at least 3 mi of displacement. The fault occurred in very Late Cretaceous or Early Paleocene Age (30).

The coal-bearing rocks of the Hams Fork region are the Cretaceous Bear River, Frontier, and Adaville Formations, and the Paleocene Evanston Formation. The Kemmerer Mine extracts coal from the Adaville Formation, which consists of a yellow-brown calcareous sandstone that weathers gray, siltstone, carbonaceous clay, and coal (30). The Adaville Formation outcrops in the Kemmerer Mine area on the eastern flanks of a major synclinal structure known as the Lazeart syncline. The western flank of this structure is vertical or overturned with a dip to the west of approximately 35°; its eastern flank dips to the west approximately 30°, but it was not deformed by the Absaroka Thrust (30). In the vicinity of the Kemmerer Mine, the average dip is 18° to the west, which is relatively steep for stripping operations and limits the depth to which a surface mine can penetrate (see Figure 44).

The lenticularity of the constituent beds of the Adaville Formation can be clearly seen in the highwall faces of the mine. Most of the coal seams exposed in the highwalls of the north-south trending pits can be observed to pinch out, split, and coalesce over the length of the pits. Changes in the lithology of partings are evident as well, with sandstones grading laterally and vertically into shales and siltstones. Figure 45 shows a detailed description of the core from Hole KCW-4-1 at the Kemmerer Mine. The coal zone of the Adaville Formation can be traced continuously over a distance of approximately 100 mi (16), but local stratigraphic variations render individual beds and partings difficult, if not impossible.

Sampling Points

Two holes were drilled at the Kemmerer Mine; unfortunately, both holes proved to be dry. Neither of these holes, located as shown in Figure 46, encountered the coal seams being mined.

Five surface waters were sampled, located as shown in Figure 46. This sampling consisted of four field determinations, and detailed laboratory analyses which were performed in duplicate.

Hydrogeology

The structural features of the Hams Fork region serve to complicate the hydrogeology such that few generalizations can be made. Recharge to the rock units in the area is primarily through direct infiltration of rainfall

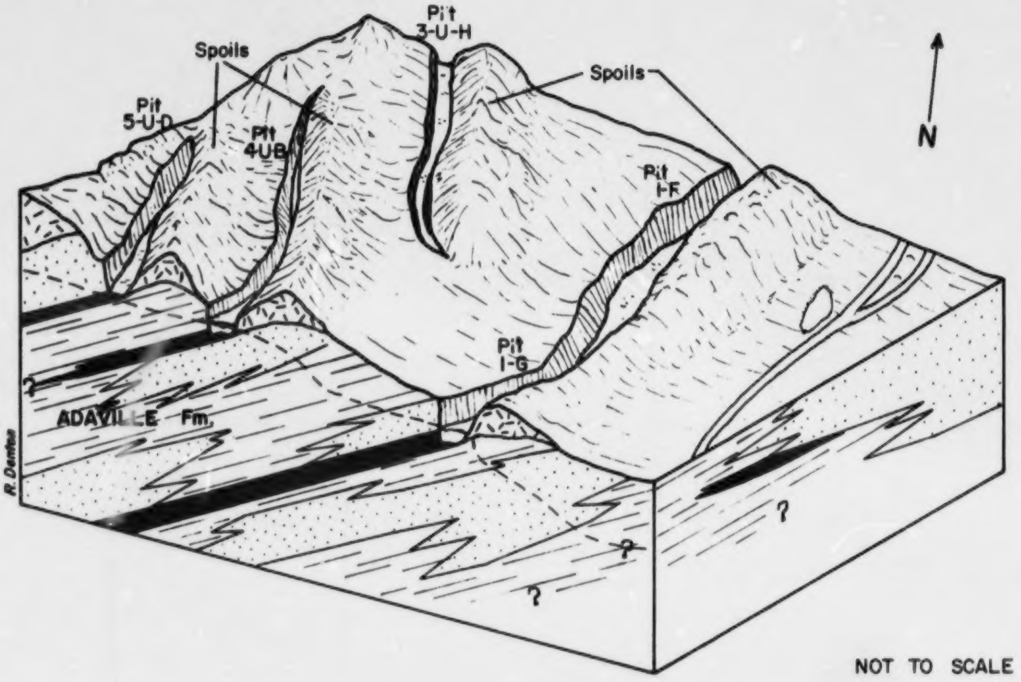

Pit
3-U-H
Spoils
Spoils
Pit
5-U-D
Pit
4UB
Pit
1-F
Pit
1-G
ADAVILLE Fm
N
?
NOT TO SCALE

Figure 44. Idealized block diagram showing major geologic features. Kemmerer Mine, Wyoming.

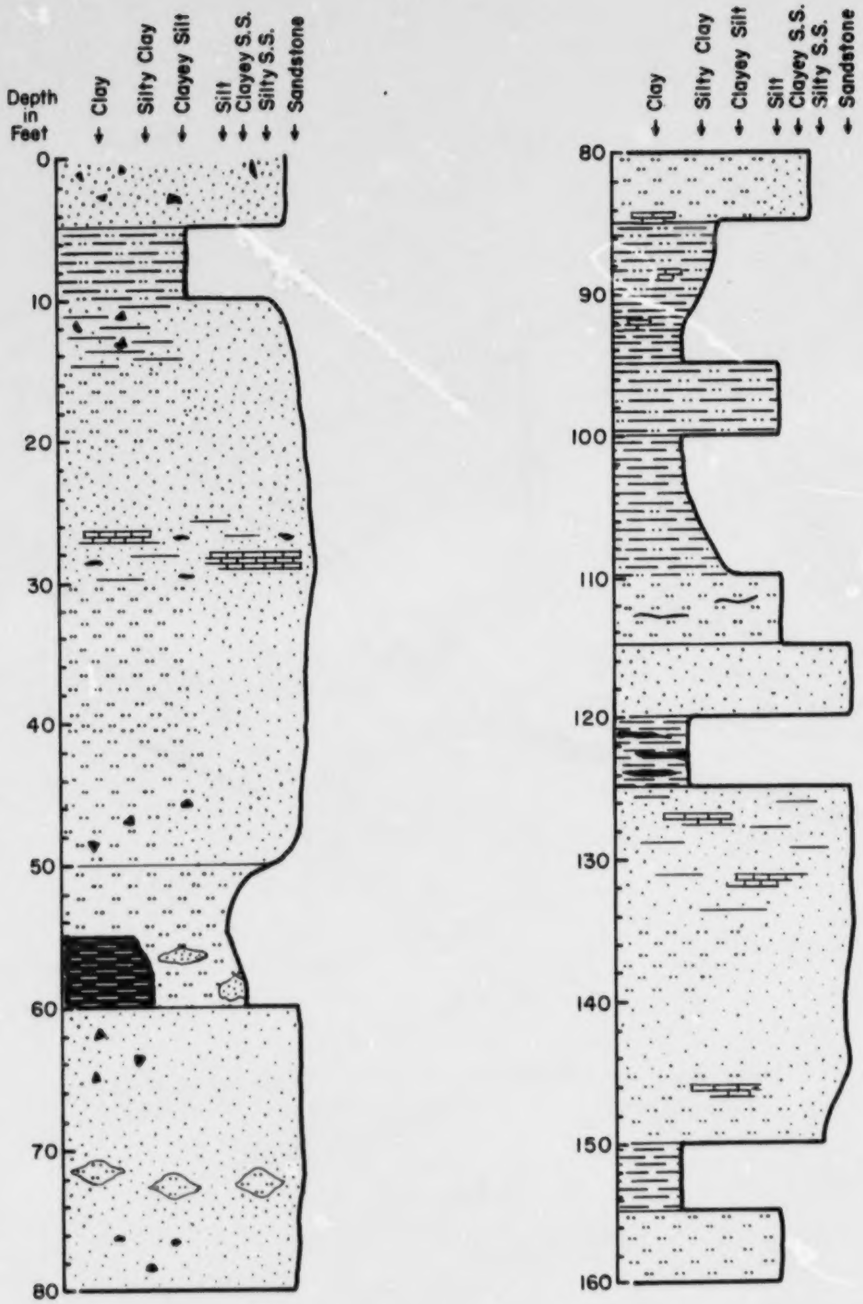

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

Figure 45. Detailed description of core from Hole KCW-4-1. Kemmerer Mine, Wyoming.

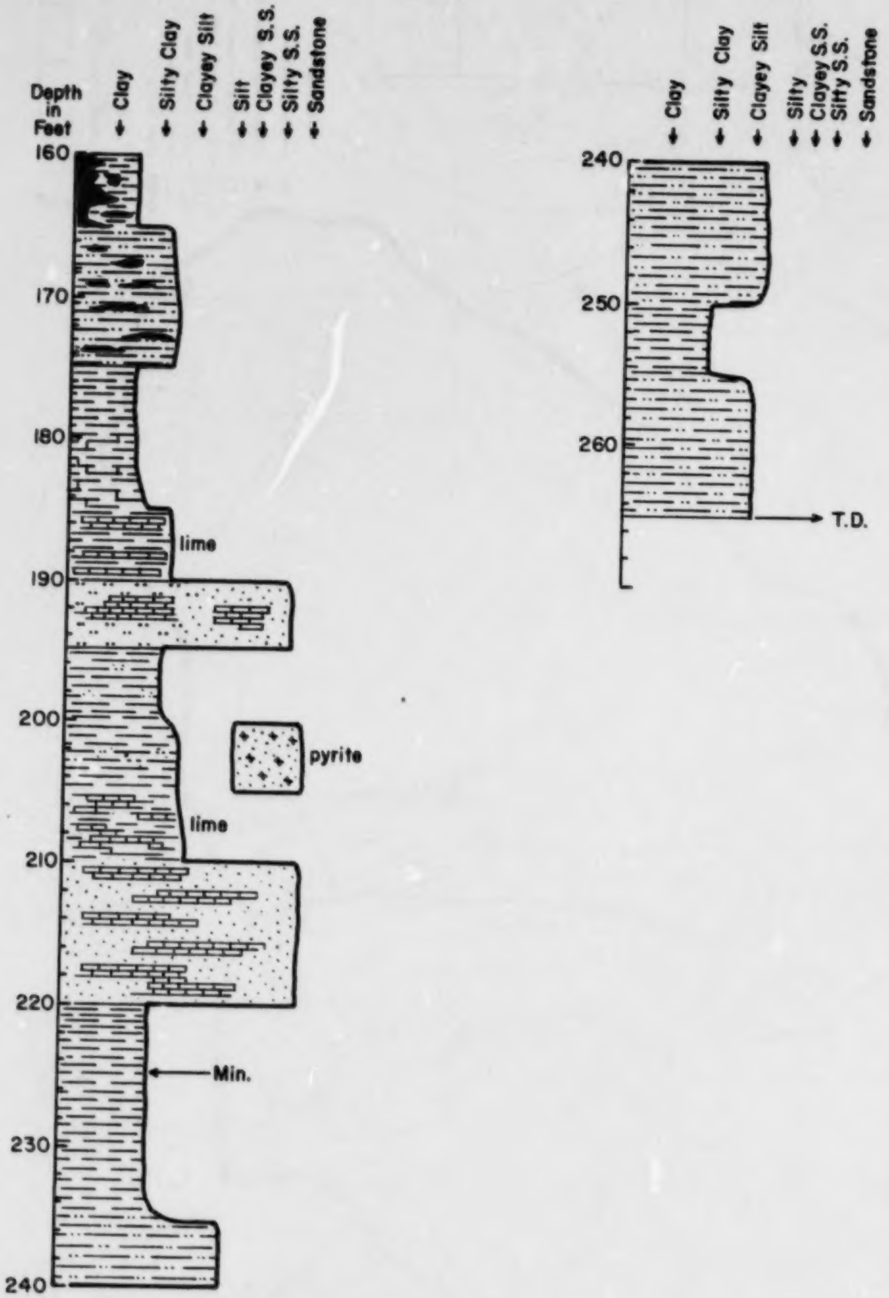

Depth in Feet
Clay
Silty Clay
Clayey Silt
Silt
Clayey S.S.
Silty S.S.
Sandstone
160
170
180
lime
190
200
pyrite
lime
210
220
Min.
230
240
Clay
Silty Clay
Clayey Silt
Silty
Clayey S.S.
Silty S.S.
Sandstone
240
250
260
T.D.

Figure 45 (Cont.). Detailed description of core from Hole KCW-4-1. Kemmerer Mine, Wyoming.

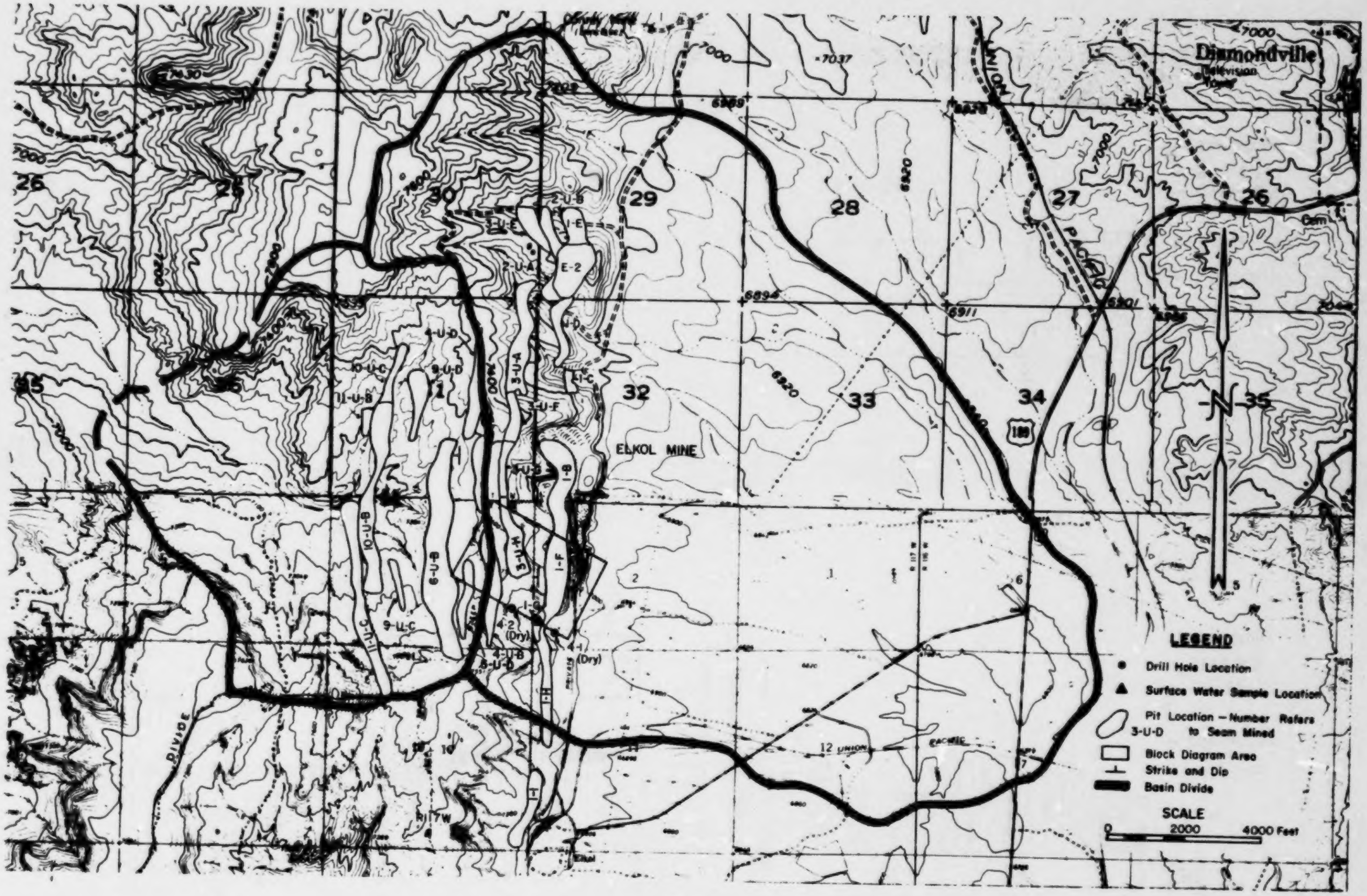

Diamondville
Television Tower
UNION PACIFIC
ELKOL MINE
26
27
28
29
30
31
32
33
34
35
25
E-2
1-E
2-U-B
2-U-A
3-U-A
3-U-E
1-B
1-F
1-C
1-D
3-U-F
4-U-D
9-U-D
10-U-C
11-U-B
10-U-B
6-U-B
9-U-C
4-2 (Dry)
4-U-B
5-U-D
(Dry)
12 UNION PACIFIC
DIVIDE
7000
7200
7400
7800
6920
6820
6894
6911
6901
7037
N
LEGEND
Drill Hole Location
Surface Water Sample Location
Pit Location – Number Refers to Seam Mined
3-U-D
Block Diagram Area
Strike and Dip
Basin Divide
SCALE
0
2000
4000 Feet

Figure 46. Sample location map. Kemmerer Mine, Wyoming.

and snowmelt; however, because one aquifer abuts or overlies another, some recharge can occur along contact zones (15).

Ground-water movement is likely to be structurally controlled and reflected in surface drainage. Some movement undoubtedly occurs between aquifers that are in contact as described above. Impoundments in the Kemmerer Mine area are common in almost all of the pits, except those excavated in Seam 3. Only Pit 3-U-A in Seam 3 was found to contain water. The origin of the perennial waters in these pits is open to conjecture; however, the low average annual precipitation and high evaporation rates in this area suggest a ground-water origin. Hole KCW-4-1 drilled on the west side of Pit 1-G was dry the entire 40 ft. A deeper hole to the east drilled to a depth of 307 ft, was also dry. The latter hole was updip and downslope from Pit 4-U-B which contained water. No water accumulated in either hole after standing open for 24 hr.

Some small, perennially flowing seeps can be seen on the highwall face of Pit 1-G, as evidenced by accumulations of ice in these zones during winter months. This fact would suggest at least some minor crossdip aquifer communication.

Ground-water discharge is likely to be represented by the above-mentioned seeps and by the perennial ponds in some pits. These ponds reportedly maintain a fairly constant elevation throughout the year, indicating that they are being fed by a ground-water source. The amount of ground-water contribution to these ponds, although constant, must be of low volume inasmuch as no surface discharge from the ponds is noted. This condition would indicate that evaporation rates are approximately equal to inflow rates. Some discharge may also occur to other basins as a result of interformational movement. In this instance, it would be possible for a particular unit to receive recharge from one basin and discharge into another basin.

Mineralogy

The lithologic composition of the core examined contained approximately 42% sandstone, 23% siltstone, 32% shale, and 3% limestone. Some pyrite and gypsum was observed.

Present in all samples were major kaolinite and major-to-minor amounts of clay-mica. Montmorillonite and vermiculite were virtually absent in all samples. Carbonates present included calcite, dolomite, and siderite which, although ubiquitous, were generally present only in small quantities. Gypsum was also present in almost all samples and comprised up to an estimated 25% of some samples. Pyrite was present in minor to trace amounts in many of the samples (see Table 14).

TABLE 14. X-RAY DIFFRACTION DATA KEMMERER MINE, WYOMING

	Pond	Pit	Pit	Pit	Pit	Pit	Pit	Pit	Pit 1-G Encrustations		Spoils	Hard Pan	Hole 4-1	Hole 4-2	Encrustations				
	10-U-C	1-G	9-U-D	1-A	4-U-F	1-B	1-A	X	Pond 1	Pond 2	4-U-F	Pit 1-G	220'-225'	40'-45'	9-U-D	1-B	4-U-F	10-U-G	1-A
Quartz	60	60	65	60	60	65	60	65	55	55	30	10-15	50	55	65	55	40	55	40
Feldspars	5	Tr	2	2	5	3	3	5	5	5	2	Tr	10	5	5	10	Tr	--	5
Kaolin	10	15-20	15	10-15	10-15	10	--	20	15	15	10	5-10	10-15	15	10	15	5	10	25
Montmorillonite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Mica	Tr	5	5	--	Tr	Tr	5	Tr	5	Tr	Tr	Tr	Tr	5	5	5	--	20	5
Dolomite	--	Tr	--	--	--	--	--	--	Tr	--	--	--	5	--	5	5	--	--	--
Calcite	5	Tr	5	5	7	--	--	Tr	--	?	--	--	--	--	--	--	--	5	5
Siderite	Tr	--	5	--	5	--	--	Tr	Tr	--	--	--	5	--	5	--	--	5	--
Gypsum	--	--	--	Tr	--	5	20	--	25	10	--	--	--	--	--	5-10	5	5	5
Pyrite	5	5	--	--	--	--	--	5	5	--	35	55	--	5-10	--	--	5	5	--
Hexahydrite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	40	--	25
CLAY FRACTION (<2μ)																			
Kaolinite	M	M	M	M	M	M	M	M	ND	ND	M	ND	M	M	ND	ND	ND	ND	ND
Illite	M	m	M	m	m	m	--	m	ND	ND	m-Tr	ND	m	m-M	ND	ND	ND	ND	ND

ND -- not determined P -- predominant (est. +80%) M -- major (est. 40-80%) m -- minor (est. 10-40%) Tr -- trace (est. 1-10%)

Water Chemistry

All waters from the Kemmerer Mine area were plotted in a vector diagram (see Figure 47 and Table 15). These samples include one surface-water sample from Pit 1-G, at the Elkol Mine, and several regional ground-water analyses from a recent study by Lines and Glass (15). The ground-water analyses from this study represent spring and well waters derived from alluvium and bedrock in the vicinity of the Kemmerer Mine.

Pit 1 was a calcium-magnesium sulfate, high-TDS water, while regional ground waters were calcium predominant, calcium-magnesium rich, low-TDS, bicarbonate waters. Bicarbonate content varies widely in these ground waters, but in no case does sulfate ever exceed the bicarbonate value. Ground water from the Hams Fork Formation in the immediate vicinity of the town of Kemmerer, is one of the most sulfate-rich ground waters noted. These waters have bicarbonate to sulfate ratio of only 1.5. By comparison, pit water from the Elkol Mine has a bicarbonate to sulfate ratio of 0.07, with a TDS content twelve times that of the local ground water.

Input Parameters

The following is a summary of the important parameters from the Kemmerer Mine that represent inputs to the development of the predictive method:

Climate. Average annual rainfall in the Kemmerer area is 9.2 in. and is fairly well distributed throughout the year. Evapotranspiration exceeds precipitation throughout the year producing a soil moisture deficit of 15.6 in.

Geology. The structural geology of the Kemmerer Mine is the most complex of any of the mine sites investigated. Mining takes place in relatively steep-dipping strata. Lenticularity of the coal beds makes correlation of core-hole data difficult.

Hydrogeology. Because of the structural complexity of the Kemmerer Mine area, the hydrogeology is not well understood. Both holes drilled on the mine property were dry; therefore, only surface-water samples were taken during this study. A recent study of ground water in the Kemmerer Mine area (15) shows that ground waters are derived from alluvium and bedrock sources.

Because coring operations showed that silty clays and shales are abundant in the stratigraphic section at the mine, it is assumed that non-alluvial aquifers occurring in the section are isolated.

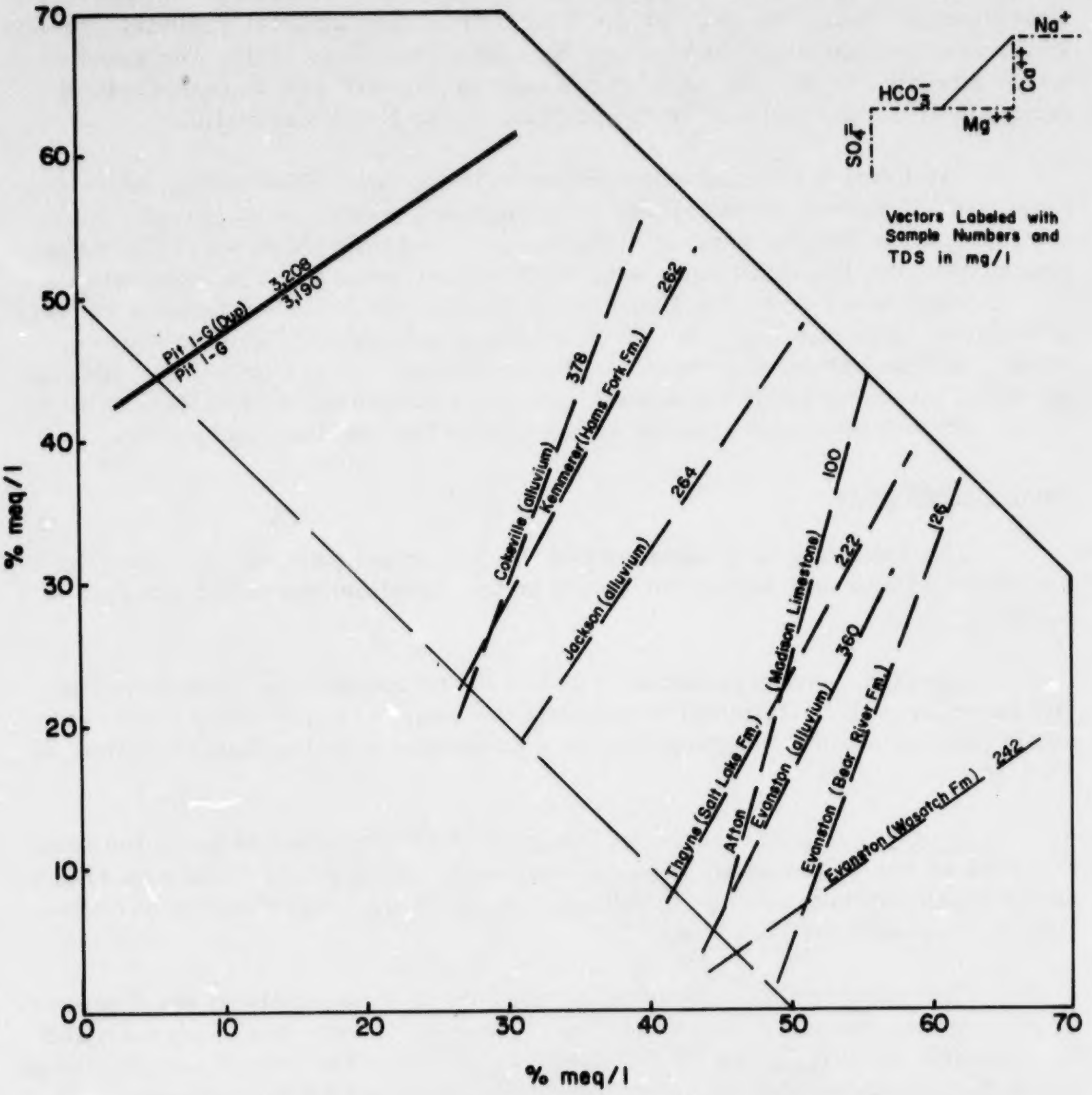


Figure 47. "Vector" diagram of water compositions. Kemmerer Mine, Wyoming. (Dashed lines from Lines and Glass (15). These analyses appear in Appendix Table C-12).

TABLE 15. WATER DATA
KEMMERER MINE, WYOMING

Samples	Pit 1-G	Pit 1-G (duplicate)
Field Measurements		
Temperature (°C)	19	19
pH	8.0	8.0
Dissolved O_2 (mg/l)	8	8
Conductivity (μmhos)	2,550	2,550
Laboratory Measurements		
Temperature (°C)	19	19
pH	8.0	8.0
Total Dissolved Solids (mg/l)	3,190	3,208
Ca^{+2} (mg/l)	382	382
Mg^{+2} (mg/l)	344	344
Na^{+1} (mg/l)	45.4	44.8
K^{+1} (mg/l)	20.1	20.1
$\overset{\circ}{Fe}$ (mg/l)	0.15	0.77
SO_4^{-2} (mg/l)	2,025	2,025
HCO_3^{-1} (mg/l)	148	147
Cl^{-1} (mg/l)	20	19

Mineralogy. The sandstones, siltstones, shales, and coals of the Adaville Formation exposed at the Kemmerer Mine contained the potentially reactive minerals calcite, dolomite, siderite, pyrite, gypsum, kaolinite, and hexahydrite. The last of these is undoubtedly secondary and results from evaporation of magnesium-sufate-rich waters at the ground surface.

Water Chemistry. A water sample taken from a pit in the Kemmerer Mine area was a high-TDS, calcium-magnesium-sulfate rich water, while regional ground water from the nearby town of Kemmerer is a low-TDS, calcium-predominant, calcium-magnesium-bicarbonate-sulfate water. Other ground waters from the area are considerably less enriched in sulfate.

WYODAK MINE

The Wyodak Mine is located approximately 5 mi east of Gillette, in Campbell County, Wyoming. The area along the eastern margin of the Powder River Basin contains one of the world's largest known coal deposits. The Wyodak Mine, in operation since 1925, is owned and operated by Wyodak Resources Development Corp.

Topographically, the area of the mine consists of low rolling hills with relief of approximately 100 ft. Several large depressions occur immediately to the west of the mine area that intermittently contain water.

Donkey Creek, which flows from west to east, is the major drainage within the immediate vicinity of the mine (see Figure 48). This stream currently carries sewage effluent from the city of Gillette eastward where it empties into the Belle Fourche River system.

Climate

The Wyodak Mine is situated in a semi-arid environment, similar to the other mine sites investigated in this study. The mean annual temperature at Wyodak, based on the Gillette station, is 45°F. Annual and daily temperature variations are large because the area is subject to both maritime Pacific air masses and continental air masses originating in Canada.

Average annual precipitation in the mine area is 15.8 in., with a large percentage occurring during the months of May and June. Summertime precipitation is in the form of showers with an occasional cloudburst. Fall and winter snows tend to be light, whereas in the springtime heavy wet snows fall with some rain.

Evapotranspiration exceeds precipitation throughout the year and is probably attributable in large part to the relatively strong winds which average approximately 13 mph.

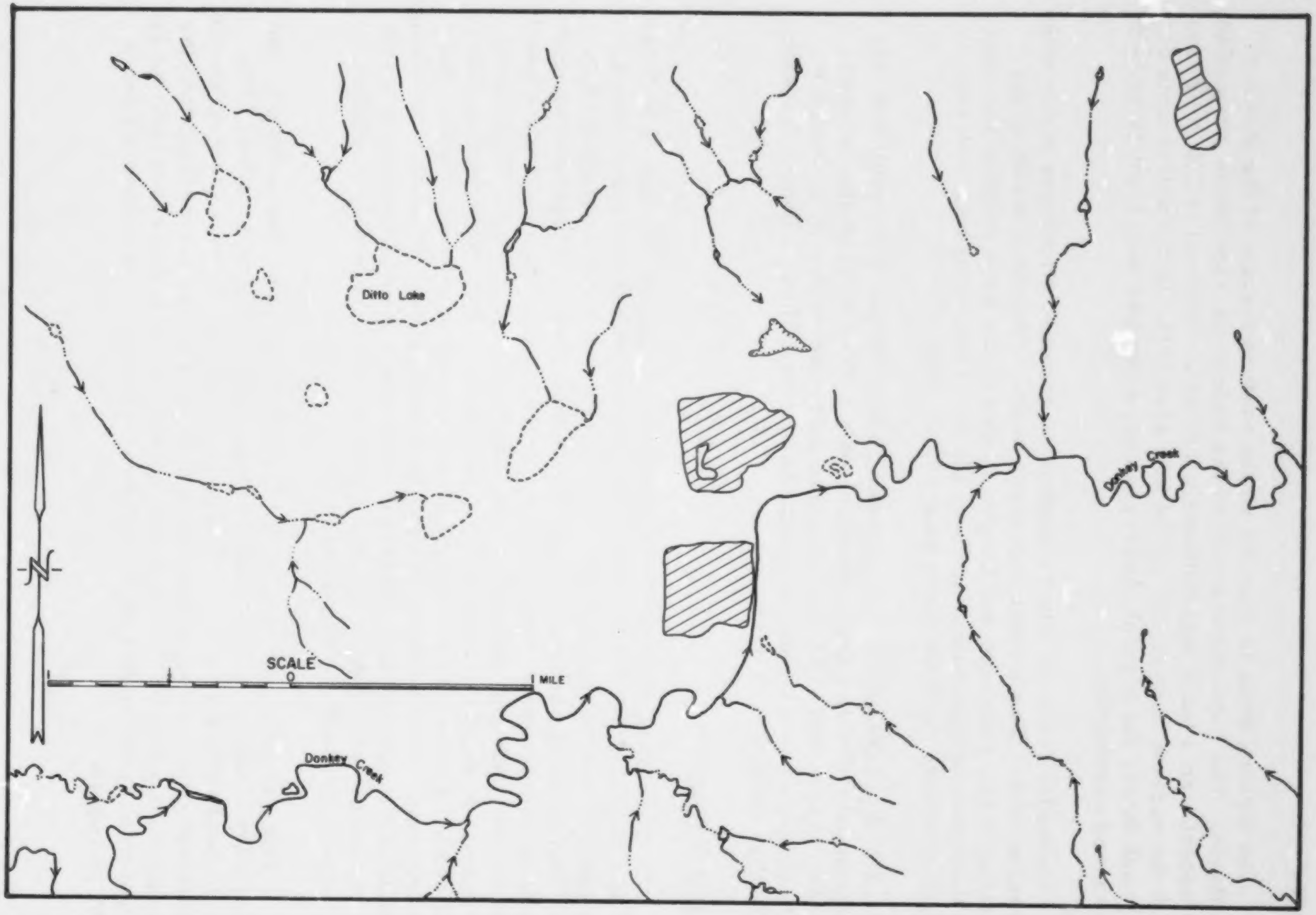

Ditto Lake
Donkey Creek
Donkey Creek
SCALE
0
1 MILE
N

Figure 48. Surface drainage in the vicinity of the Wyodak Mine, Wyoming.

Geology

The Wyodak Mine is situated on the eastern margin of the Powder River Basin. The coals form a part of the Paleocene Fort Union Formation, which underlie an area of approximately 800 mi^2. The coal is 200 ft or less beneath the surface in over 117 mi^2 of this area (31). In the active area of the Wyodak Mine, the Wyodak-Anderson coal seam has only from 15 to 25 ft of weathered overburden.

No major faults or other complicated geologic structures occur within the mine area. The Wyodak-Anderson seam, which is a result of the coalescing of the Anderson and Canyon seams in the area south of the mine, has a thickness of approximately 90 to 100 ft. These coal beds and associated bedrock units dip toward the west at less than 1°.

The Wyodak-Anderson coal seam is of subbituminous rank and, although comprised of two units, displays only a very thin parting between units (see Figure 49). The two units are somewhat different in fracture density with the upper, Anderson unit, appearing to have a higher fracture density than the lower, Canyon unit.

Sampling Points

Samples were recovered from a highwall face on the east wall of the mine (see Figure 50). The Wyodak coal seam is in direct contact with a fairly uniform dark-gray, fissile, carbonaceous shale approximately 2-ft thick. Stringers of coal can be seen within this shale. A highly weathered, essentially homogeneous sandstone unit overlying the shale contains a basal conglomeratic unit approximately 3-in. thick (see Figure 51). This latter unit consists of angular, 1- to 1.5-in. sandstone fragments with fine, interstitial sand. A network of very fine fractures can be seen throughout the sandstone unit. These fractures contain a white sulfate mineral. Overlying the shale and conglomeratic sandstone units at the sample location is a thin layer of unconsolidated material composed of large fragments of clinker, coal, clay, and poorly sorted sand.

Water samples were collected from the south pit, the north pit, and from Donkey Creek at a point immediately to the south of the mine. The water in Donkey Creek appeared to be moving partly through the overburden and partly through the upper coal directly, prior to the discharging into the pit area. A sample of water from the north pond was also collected, but the data were not used because this pond receives recirculated waters from a nearby power plant.

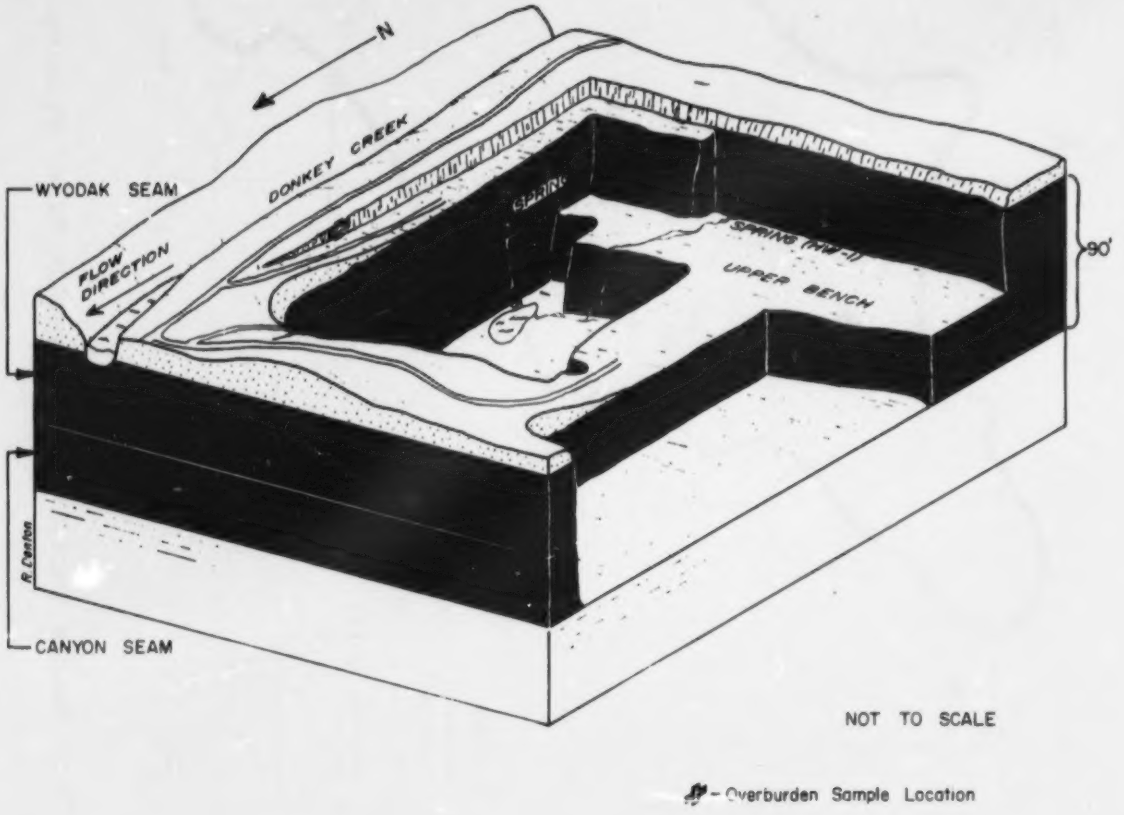

N
DONKEY CREEK
WYODAK SEAM
FLOW DIRECTION
SPRIN
SPRING (NW-1)
UPPER BENCH
90'
R. Canyon
CANYON SEAM
NOT TO SCALE
- Overburden Sample Location

Figure 49. Idealized block diagram showing major geologic features. Wyodak Mine, Wyoming.

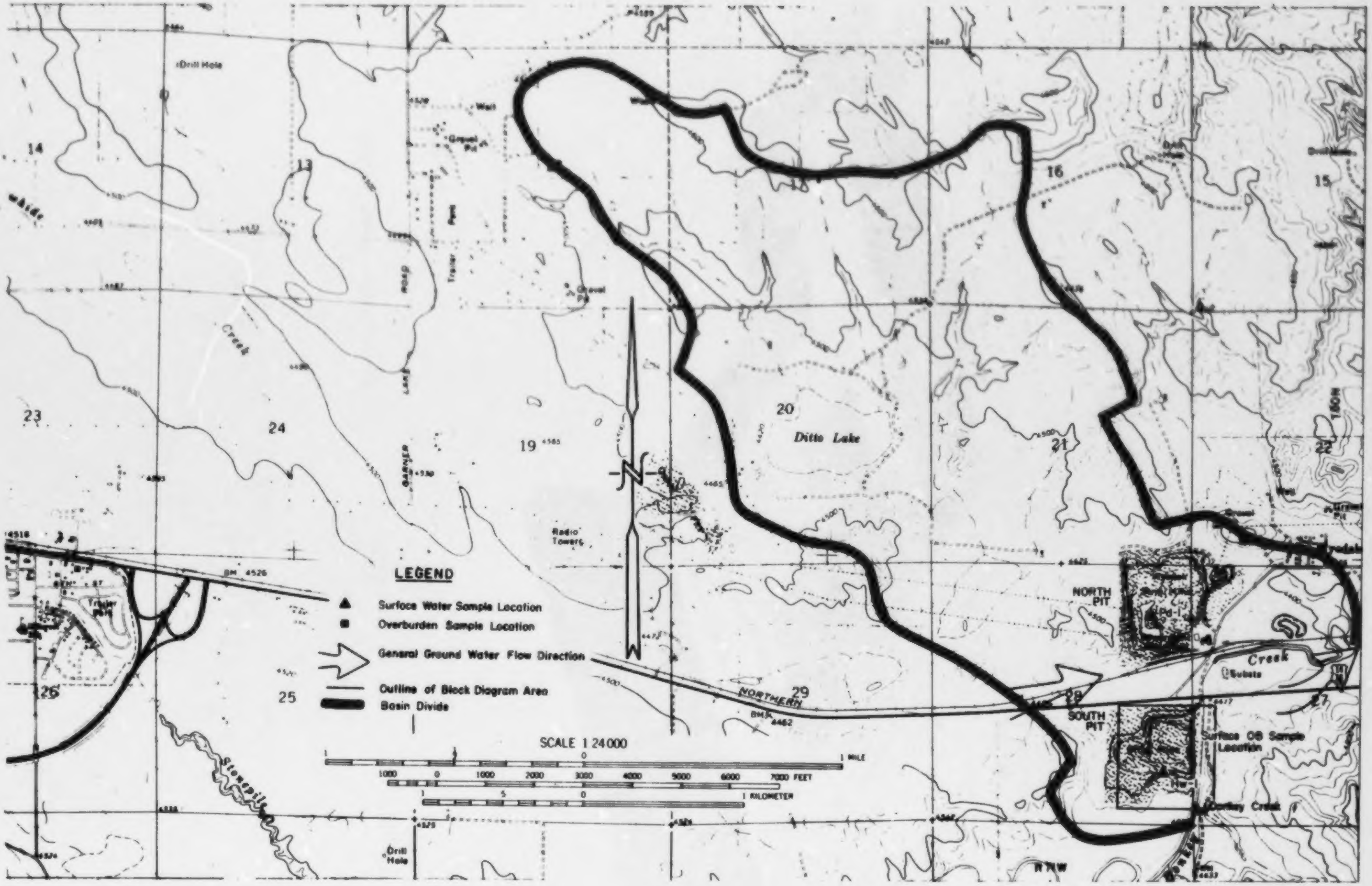

LEGEND
Surface Water Sample Location
Overburden Sample Location
General Ground Water Flow Direction
Outline of Block Diagram Area
Basin Divide
SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
Ditto Lake
NORTH PIT
SOUTH PIT
Surface OB Sample Location
Donkey Creek
Creek
NORTHERN
Radio Towers
Drill Hole
Gravel Pit
Trailer Park
Well
GARNER LAKE ROAD
Creek
Stonepile
R 72 W
T 50 N
13
14
15
16
19
20
21
22
23
24
25
26
27
28
29

Figure 50. Sample location map. Wyodak Mine, Wyoming.

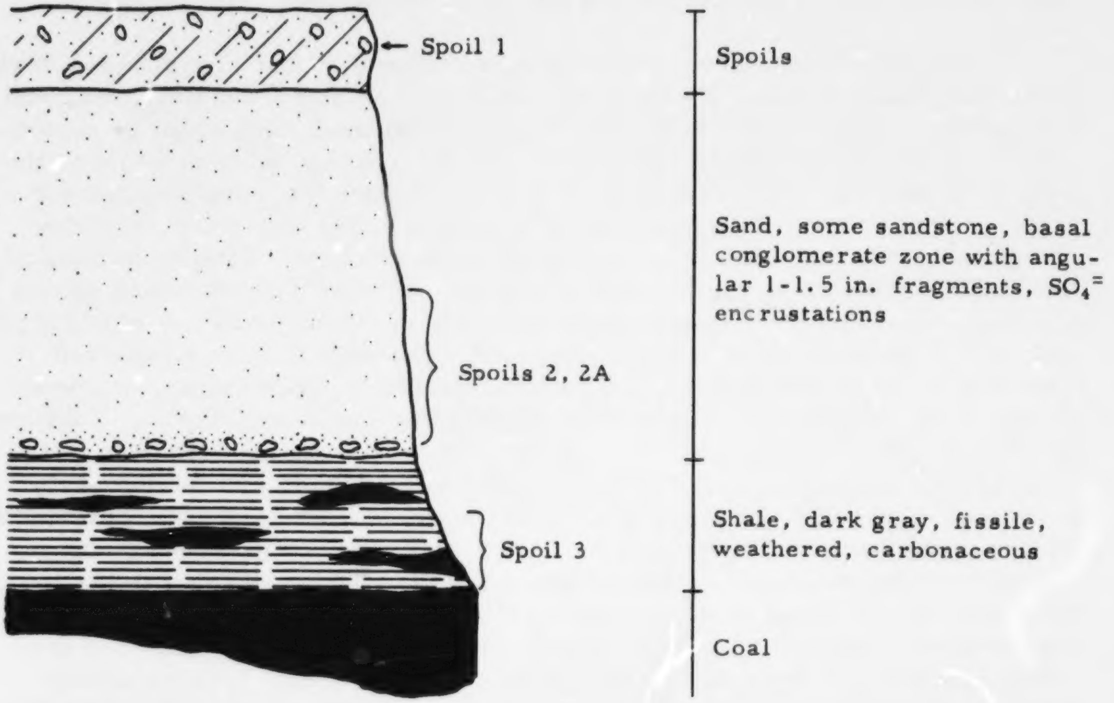

Spoil 1
Spoils 2, 2A
Spoil 3
Spoils
Sand, some sandstone, basal conglomerate zone with angular 1-1.5 in. fragments, $SO_4^=$ encrustations
Shale, dark gray, fissile, weathered, carbonaceous
Coal

Figure 51. Description of overburden materials. Wyodak Mine, Wyoming.

Hydrogeology

Ground-water recharge in the area can be regarded as coming from direct infiltration of rainfall and snowmelt, and to some degree through surface water sources in the area. The majority of wells in the surrounding area are less than 300-ft deep and have water levels less than 200-ft deep. These wells are constructed primarily in unconfined aquifers with only a few constructed in semiconfined-to-confined aquifers.

Ground-water movement is basically from west to east with some dispersion to the north in the area immediately east of the mine site (12). The easterly flow direction follows the surface drainage rather closely.

No drilling was determined to be warranted at this site because of the extremely large amount of exposure, relatively confined working area, and exceptionally thin overburden. The Wyodak-Anderson coal seam is reportedly a significant aquifer in the Gillette area, yielding water to wells at the rate of 10 to 50 gpm (32). It is therefore likely that the coals account for some ground-water movement through the area. The water that was observed entering the south and east walls of the south pit, cannot, however, be totally attributed to ground-water origins. Donkey Creek, which drains the area south of the south pit, flows within several hundred feet of the highwall and is believed to be the source of the mine water. The streambed over the entire length of the creek, and in proximity to the mine, has been dredged out, and the sediments were piled along the streambanks. Coal can be seen to comprise some of the dredged material, and the stream itself is flowing approximately 15 ft below the natural land surface in an obviously man-made cut. The presence of coal in the dredged material, and the depth of stream bottom, indicates that the stream channel in this area has been cut through the overburden; the water is now in direct contact with the top of the coal. From these observations it is concluded that stream water is moving downward through the Wyodak seam to the top of the canyon, then moving laterally along the parting to emerge at the highwall. It is not likely that water from the Wyodak-Anderson aquifer comprises a significant percentage of this water.

Ground-water discharge was not definitely found within the immediate area of the mine, although some of the waters entering the south pit, and to some extent the minor seeps in the north pit, are ostensibly ground-water related. Most shallow ground-water discharge appears to occur more to the southeast, in the Belle Fourche River drainage.

Mineralogy

The lithology of the overburden at Wyodak Mine ranged from a calcareous sandstone to an argillaceous siltstone. Gypsum was detected in the sandstone and pyrite in the coal. Some iron staining was noted in the shale above the coal, indicating the presence of what could have been pyrite. X-ray diffractometer scans revealed the major minerals to be quartz, feldspar, kaolinite, mica, calcite, and gypsum (see Table 16). The clay-size fractions of most samples contained major kaolinite, major calcite, and quartz with minor clay-mica. Montmorillonite and vermiculite were virtually absent.

Water Chemistry

Surface-water compositions from the Wyodak Mine area are plotted in Figure 52. The plots are corrected for chlorine content, which was unusually high in the Donkey Creek and highwall pit samples (see Table 17). These surface samples can be categorized as calcium-magnesium-sulfate, high-TDS waters. Chlorine enrichment occurs only in the surface water and is due to upstream pollution from a sewage treatment plant. Because the highwall pit water is derived from Donkey Creek, it displays the same chlorine contamination.

No ground-water samples were collected at the Wyodak Mine. Instead, a literature search was conducted for ground-water compositions in the area to test the feasibility of simplifying the data-gathering phase of the predictive method. Two regional investigations, one of the Powder River Basin water resources (18) and another on ground water in the Gillette area (20) were utilized. The literature revealed that ground waters in the vicinity of the mine are derived from the lower Wasatch and upper Fort Union Formations. The literature also revealed that sodium-sulfate and sodium-bicarbonate waters are dominant in the Wasatch Formation, while sodium-bicarbonate and, to a lesser extent, sodium-sulfate waters are dominant in the Fort Union Formation. The published water quality map of the Powder River Basin shows a low TDS, sodium-bicarbonate ground water from the Fort Union Formation to be predominant in the immediate vicinity of the town of Wyodak, while a high-TDS, magnesium-sulfate water, from the Wasatch Formation, is predominant southwest of the mine area.

Input Parameters

The following is a summary of the important parameters from the Wyodak Mine that represent inputs to the development of the predictive method:

Climate. Evapotranspiration exceeds precipitation throughout the year. Average annual precipitation in the mine area is 15.8 in. with a large percentage occurring as cloudbursts.

TABLE 16. X-RAY DIFFRACTION DATA
WYODAK MINE, WYOMING

	Spoils 2	Sandy Overburden 3	Sandy Overburden 4	Overburden Shale 5	Spoils 7
Quartz	40	50	55	40	60
Feldspars	30	10-15	10	15	--
Kaolin	10	10	10	35	40
Mica	Tr	2	Tr	Tr	--
Calcite	Tr	5	Tr	--	--
Gypsum	5	--	10	--	--
		CLAY FRACTION (<2 μ)			
Kaolinite	M	M	M	M	M
Illite	m	m	m	m	m

ND -- not determined

P -- predominant (est. +80%)

M -- major (est. 40-80%)

m -- minor (est. 10-40%)

Tr -- trace (est. 1-10%)

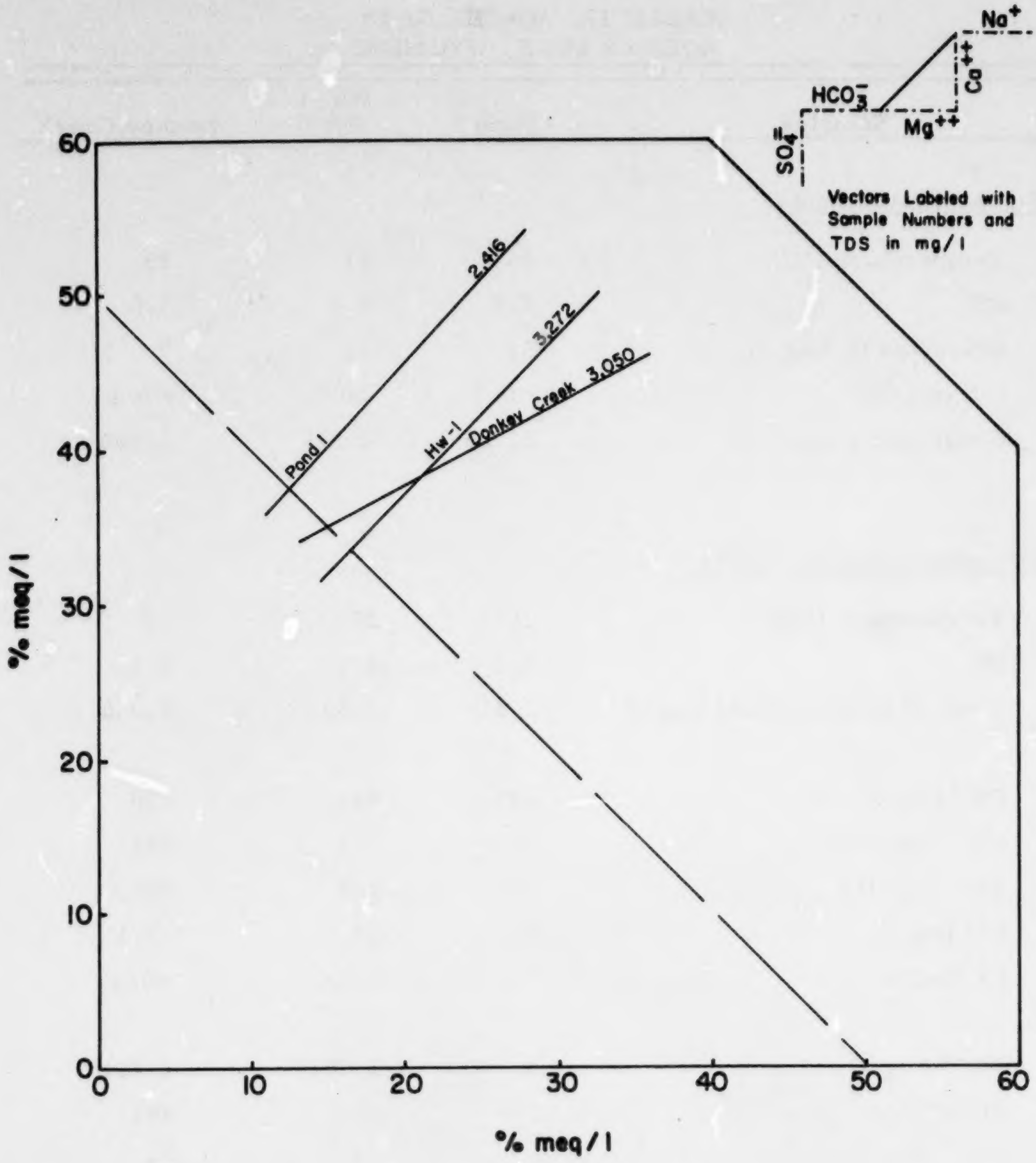


Figure 52. "Vector" diagram of water compositions. Wyodak Mine, Wyoming.

TABLE 17. WATER DATA
WYODAK MINE, WYOMING

Samples	Pond 1	HW-1 Pit 1	Donkey Creek
Field Measurements			
Temperature (°C)	26	21	29
pH	7.4	9.4	7.0
Dissolved O_2 (mg/l)	5	3	7
H_2S (mg/l)	<0.1	<0.1	<0.1
Conductivity (μmhos)	2,725	2,825	3,900
Laboratory Measurements			
Temperature (°C)	26	20	29
pH	7.8	7.4	8.2
Total Dissolved Solids (mg/l)	2,416	3,394	3,050
Ca^{+2} (mg/l)	295	425	250
Mg^{+2} (mg/l)	164	249	294
Na^{+1} (mg/l)	276	338	366
K^{+1} (mg/l)	25	17.9	20.1
Fe° (mg/l)	<0.1	0.42	<0.1
SO_4^{-2} (mg/l)	1,390	1,701	1,714
HCO_3^{-1} (mg/l)	545	564	493
CO_3^{-2} (mg/l)	--	--	--
Cl^{-1} (mg/l)	19	263	203

Geology. The geology in the vicinity of the Wyodak Mine is structurally simple, consisting of the flat-lying sandstones, shales, coals, and basal conglomerates.

Hydrogeology. No aquifers occur in the overburden in the vicinity of the mine; however, a stream in contact with the coal provides water which moves laterally into the mine as springs in the highwall.

Mineralogy. Mineralogy of samples taken from the overburden include the potentially reactive minerals calcite, gypsum, and kaolinite. Although no pyrite was detected by x-ray diffraction, iron staining in the shale above the coal was observed in the field, and pyrite was observed in the coal.

Water Chemistry. Ground water in the immediate vicinity of the Wyodak Mine is a low-TDS, sodium-bicarbonate type, while surface water at the mine is a high-TDS, calcium-magnesium-sulfate type. In addition, Donkey Creek, and consequently the highwall pit water, contain abnormally high concentrations of chlorine.

COLSTRIP MINE

The Colstrip Mine was selected for investigation to provide an additional site to test the predictive method with minimum field effort. Fortunately, extensive related data was available for baseline and comparative purposes. This mine, located immediately east of the town of Colstrip, in Rosebud and Custer Counties, Montana, extracts coal from the Rosebud coal seam of the Tongue River Member of the Fort Union Formation. The mine is owned by Montana Power Co. and operated by a subsidiary, the Western Energy Co.

The topography in the mine area consists of low-lying northwest-southeast trending hills of less than 3,600-ft elevation. Relief in the area ranges to 400 ft.

Drainage within the mine area is east-southeast from the east side of the mine and essentially north through the East Fork Armells Creek on the west side of the mine. All streams are currently intermittent, although, based on the width of the flood plain, Armells Creek must have received rather large or continuous flows at one time in the recent geologic past. Figure 53 shows the surface drainage pattern in this area.

Climate

The climate in the Colstrip Mine area can be classified as semi-arid. The average annual precipitation is 15.8 in., with greater than 50% of this

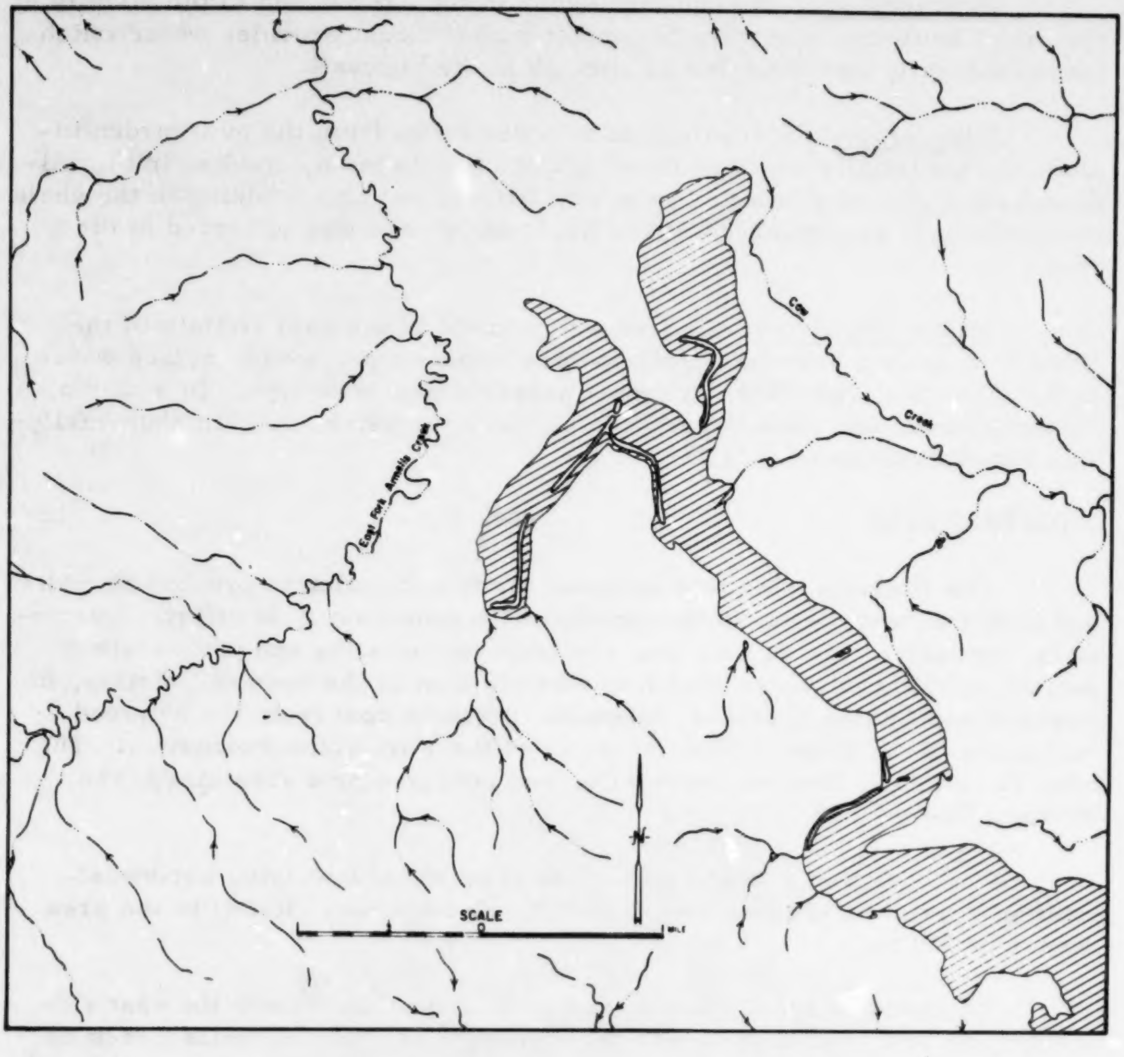

Cow Creek
East Fork Armells Creek
N
SCALE
0
1 MILE

Figure 53. Surface drainage in the vicinity of the Colstrip Mine, Montana.

occurring from May through September. The average annual temperature is 45.9°F.

Geology

The Colstrip Mine is situated in the northern part of the Powder River Basin, along the northeast flank of a broad synclinal trough that trends north-northwest within the basin, and has a southeastward plunge (33). Relatively few faults exist, and these have very small displacements.

A gentle anticlinal structure exists in the southern part of the mine which places the currently active pit in a small basin structure. Although two major coal beds occur within the Colstrip Mine area--the Rosebud and McKay beds--only the upper Rosebud is being stripped. The Rosebud seam averages approximately 25-ft thick and has a gradient to the south. The Rosebud seam is separated from the McKay by approximately 60 ft of interburden, although the interburden can range from 3 to 60 ft within the coal region (see Figure 54).

The overburden in the Colstrip Mine area ranges between 50 and 100 ft. It consists of silty shales and a fine-grained sandstone that is thinly bedded with some calcareous concretions (see Figure 55).

Sampling Points

Samples were collected in Areas D and E (see Figure 56). Area D is an old inactive area formerly mined by the Burlington Northern Railroad in the late 1930's and early 1940's. The overburden at this site is composed of Fort Union Series materials. Two surface water samples and a spring sample were collected from this area. An overburden sample was collected upgradient from the spring sample, and the surface water samples were collected from exposures in the southern part of Area D (see Figure 56).

Area E is stratigraphically similar to Area D, but currently active. Three overburden samples and one surface water sample were taken sequentially upward from the coal bed in Area E.

Hydrogeology

Because of the horizontal nature of strata in the Colstrip Mine area, recharge to the ground-water system occurs by infiltration of precipitation. The intermittent streams in the area contain alluvial deposits that are generally less than 40-ft thick. Any recharge to underlying sediments from these deposits would be minimal. In one location along the East Fork of Armells Creek, southwest of the mine, alluvial materials are in direct contact with the coals and assuredly provide a source of recharge to the coal

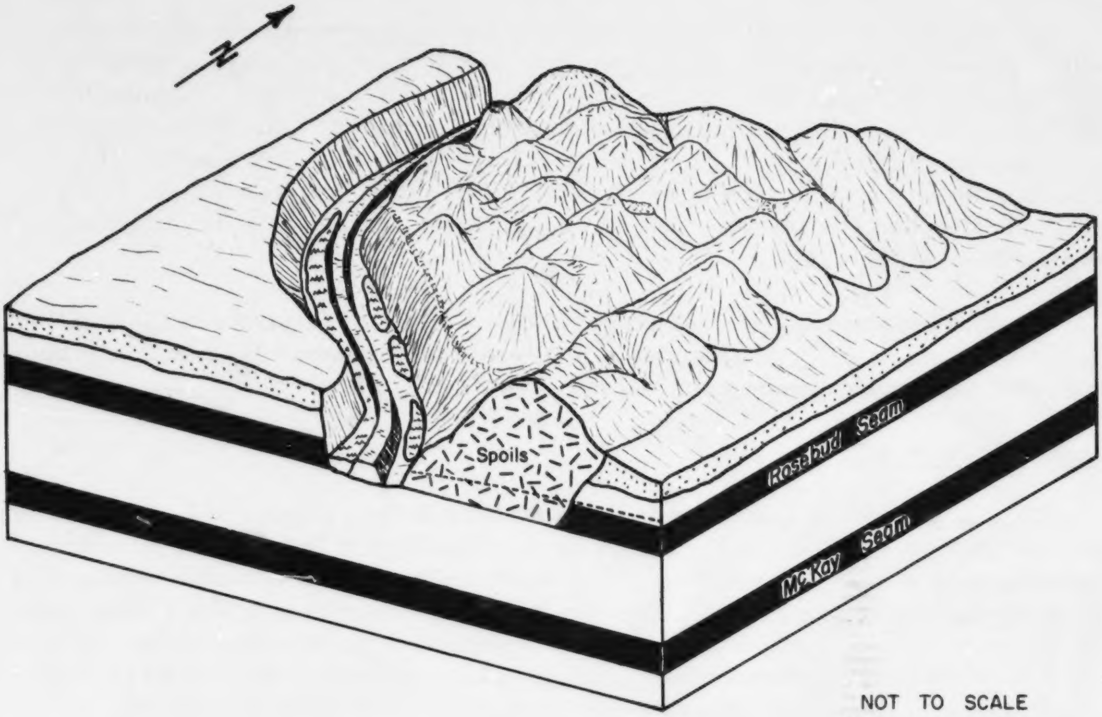

N
Spoils
Rosebud Seam
McKay Seam
NOT TO SCALE

Figure 54. Idealized block diagram showing major geologic features. Colstrip Mine, Montana.

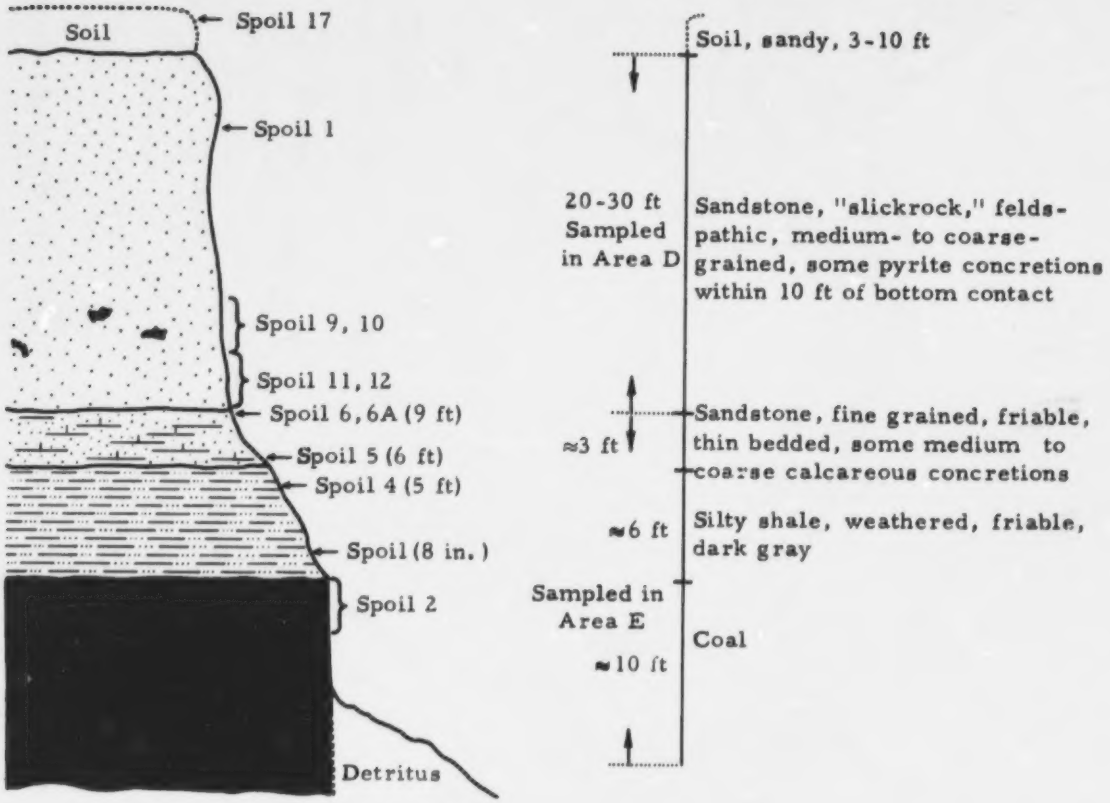

Soil
Spoil 17
Spoil 1
Spoil 9, 10
Spoil 11, 12
Spoil 6, 6A (9 ft)
Spoil 5 (6 ft)
Spoil 4 (5 ft)
Spoil (8 in.)
Spoil 2
Detritus
Soil, sandy, 3-10 ft
20-30 ft
Sampled
in Area D
Sandstone, "slickrock," feldspathic, medium- to coarse-grained, some pyrite concretions within 10 ft of bottom contact
≈3 ft
Sandstone, fine grained, friable, thin bedded, some medium to coarse calcareous concretions
≈6 ft
Silty shale, weathered, friable, dark gray
Sampled in
Area E
≈10 ft
Coal

Figure 55. Composite overburden stratigraphy, Areas D and E. Colstrip Mine, Montana.

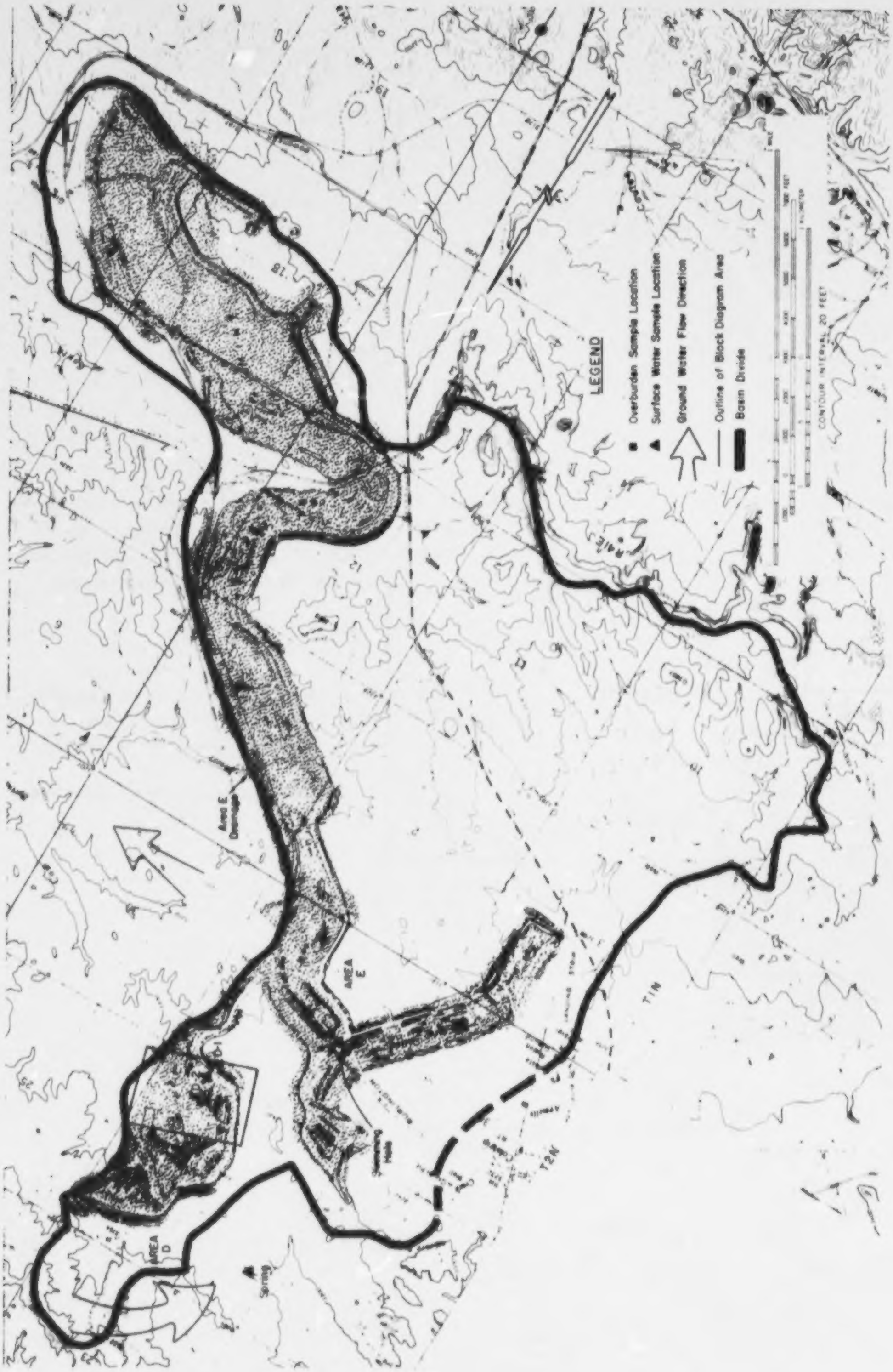

LEGEND
Overburden Sample Location
Surface Water Sample Location
Ground Water Flow Direction
Outline of Block Diagram Area
Basin Divide
CONTOUR INTERVAL 20 FEET
AREA D
AREA E
Area E Drainage
Spring
T1N
T2N

Figure 56. Sample location map. Colstrip Mine, Montana.

aquifer during periods of high flow. Recent studies of the mine area by Van Voast and Hedges (34) showed that the shallow ground-water system is responsive to surface hydrologic conditions. This was especially true where observation wells located in the spoils area recorded rises in level with the filling of impoundments from rainfall and snowmelt.

Ground-water movements in the Colstrip Mine appear to be in opposite directions (34). In the northern part of the mine the ground water is moving south, and in the southern part of the mine it is moving north. These movements are directly related to the geologic structure described earlier that creates a small basin in the mine area. Ultimately, the movement is eastward. Ground-water discharge is occurring in the streambed of the East Fork of Armells Creek, and to eastern and northern outcrops occurring in intermittent streambeds.

Mineralogy

The mineralogy and lithology of the Colstrip Mine were obtained from highwall grab samples at the various lithologic units above the coal. X-ray diffractometer scans revealed dolomite to be the major carbonate, although calcite was generally present and siderite was rare. Gypsum was present in many samples, and pyrite nodules were common in several locations (see Table 18). In a road embankment cut through a spoil pile, most of the pieces of coal were surrounded by a halo of iron-stained material several inches thick. This condition probably indicates the oxidation of pyrite associated with the coal. X-ray analysis of the clay fraction revealed the major clay to be kaolinite with minor clay-mica. Several samples also contained major montmorillonite.

Water Chemistry

Vector plots for waters sampled at the Colstrip Mine during this study and during the recent study by Van Voast and Hedges (35) are shown in Figure 57.

The three surface water samples (D-1, D-2, and a swimming hole) all had similar compositions (Table 19). All were high in TDS and enriched in magnesium relative to calcium. The predominant anion was sulfate. Sample D-2, representative of spoil water, was higher in TDS and had considerably stronger ionic strength ($\mu = 0.124$) than highwall pit water D-1 ($\mu = 0.081$), which was representative of shallow ground water. While the actual ionic strengths cannot be used as a measure of contamination, due to evaporation concentration of surface waters, the relative ionic strengths at least indicated that the spoil water is more highly mineralized than shallow ground water.

TABLE 18. X-RAY DIFFRACTION DATA COLSTRIP MINE, MONTANA

	Section E Sandstone in Overburden	Coal	Overburden Sandstone Concretion	Spoils		Area E Encrust.	Iron-Rich Sandstone	Iron-Stained Fragment from Spoils	Area D Spoils	
				7	7A				14	15
Quartz	50	30	35	40	45	40	30	35	50	30
Feldspars	5-10	--	2-5	5	10	Tr	5	--	10	10
Kaolin	5-10	5-10	5	5-10	10	5	Tr	5-10	15	5-10
Montmorillonite	Tr	--	--	--	--	--	--	--	--	--
Mica	5	--	Tr	5	5	Tr	Tr	Tr	Tr	Tr
Dolomite	10	--	5-10	10	10	35	?	5	25	50
Calcite	5	--	--	5	--	10	--	--	Tr	2-5
Siderite	--	--	--	--	--	--	10	--	--	--
Gypsum	--	--	--	10	35	5	--	Tr	--	--
Pyrite	--	--	50	--	--	--	35	30	--	--
CLAY FRACTION ($<2\mu$)										
Kaolinite	M	M	ND	M	M	M	m	M	M	M
Illite	m	--	ND	m-M	m	m-M	M	m	m-Tr	m
Montmorillonite	M	--	ND	Tr	--	Tr	Tr	--	M	Tr
Vermiculite	--	--	ND	--	--	Tr	--	--	--	--

ND -- not determined P -- predominant (est. +80%) M -- major (est. 40-80%) m -- minor (est. 10-40%
Tr -- trace (est. 1-10%)

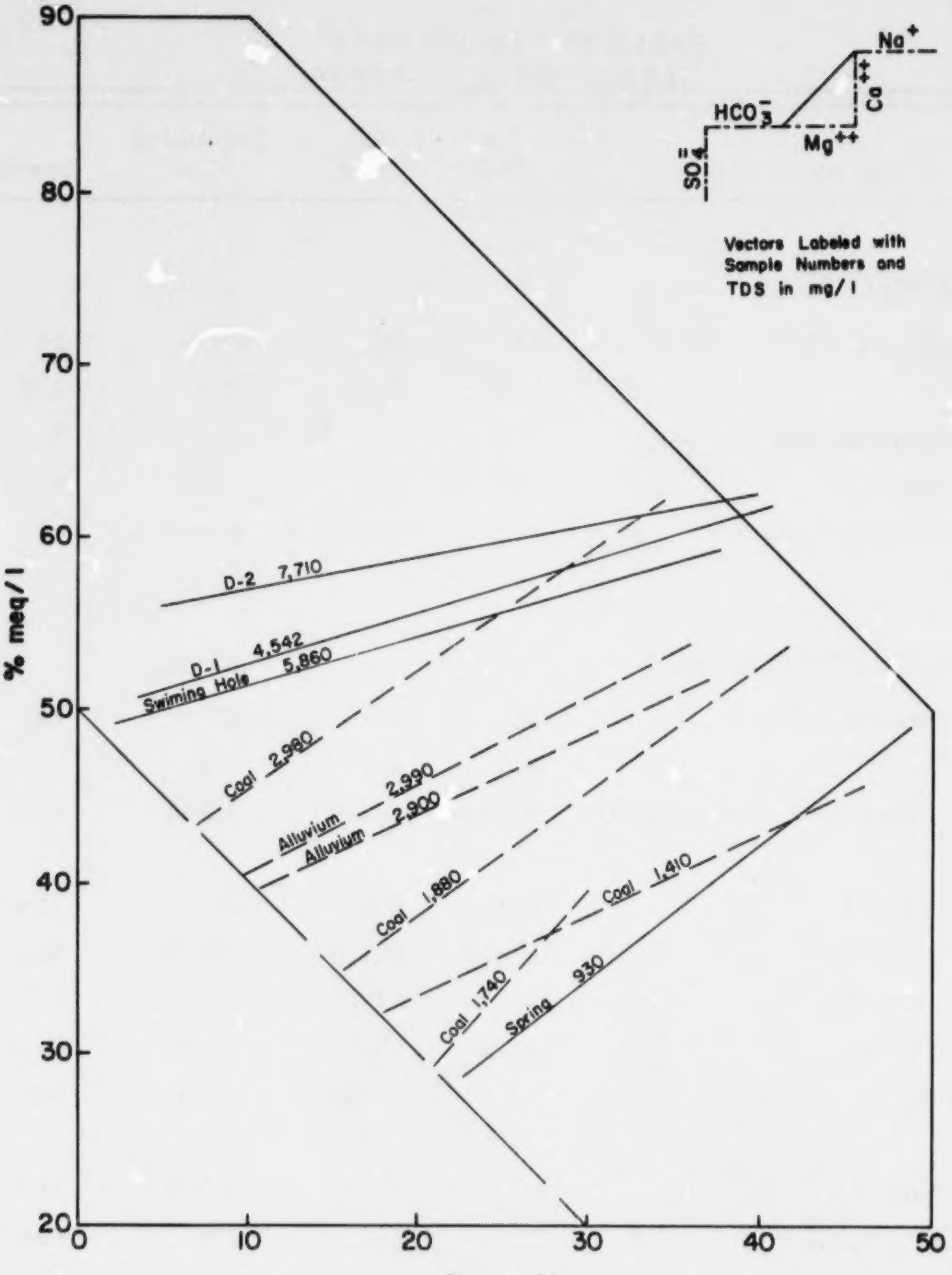


Figure 57. "Vector" diagram of water compositions. Colstrip Mine, Montana. (Data for dashed lines from Van Voast and Hedges) (35).

TABLE 19. WATER DATA
COLSTRIP MINE, MONTANA

Samples	Pit D-1	Pit D-2	Swimming Hole	Spring
Field Measurements				
Temperature (°C)	22	24	25	21
pH	7.8	8.0	7.9	7.7
Dissolved O_2 (mg/l)	9	0	6	9
H_2S (mg/l)	<0.1	--	<0.1	<0.1
Conductivity (μmhos)	1,150	6,025	4,450	--
Laboratory Measurements				
Temperature (°C)	21	26	23	19
pH	7.8	8.0	7.9	7.7
Total Dissolved Solids (mg/l)	4,542	7,710	5,680	930
Ca^{+2} (mg/l)	283	265	319	119
Mg^{+2} (mg/l)	578.0	864.0	696.0	92.5
Na^{+1} (mg/l)	11.4	219.0	151.0	21.1
K^{+1} (mg/l)	18.4	45.9	18.2	8.12
$\mathrm{F}\mathring{\mathrm{e}}$ (mg/l)	<0.1	<0.1	<0.1	<0.1
SO_4^{-2} (mg/l)	3,015	5,043	3,769	397
HCO_3^{-1} (mg/l)	250	549	175	401
Cl^{-1}	9	22	18	5

The spring water sample was much weaker than the other waters sampled in this study, had a considerably higher bicarbonate content than surface water samples, and had much lower magnesium/calcium ratio. This spring sample seems to represent an unmineralized end member in the series of waters shown in Figure 57 and may represent the ground water least affected by the mining operation; i. e., least contaminated by sulfate-rich surface waters. The fact that this water existed in an unmineralized state, close to the mine, indicates ionic isolation of at least this one aquifer by shale or clay beds in the stratigraphic section. This allows the spring waters to retain inherent chemical characteristics despite sulfate-rich waters nearby.

Additional water analyses by Van Voast and Hedges (34) showed them to lie between the spring and surface waters in TDS, ionic strength, and the bicarbonate/sulfate ratio (Appendix Table C-11). Water analyses from both the McKay and Rosebud seams, as well as two alluvial samples, are plotted in Figure 57. The gradation of weak bicarbonate spring water to strong sulfate surface water suggests that the shallow alluvial water is probably already influenced by sulfate production from the mining operation.

Input Parameters

The following is a summary of the important parameters from the Colstrip Mine that represent inputs to the development of the predictive method:

Climate. The Colstrip Mine area is located in a semi-arid climatic region having an annual precipitation of 15.8 in., with 77% occurring from May through October. Evapotranspiration exceeds precipitation throughout the year resulting in an average soil moisture deficit of 23.5 in.

Geology. The geology of the Colstrip Mine area is structurally simple. For the area under investigation, the strata of sandstone, shale, and coal are nearly horizontal.

Hydrogeology. Ground-water configurations in the study area include both unconfined and confined aquifers. Shallow ground water in the overburden above the Rosebud coal seam resides in unconfined sandstones and alluvium. The coal seam aquifers are osmotically isolated from adjacent strata by shale and clay layers. Beneath the coals, a series of sandstone aquifers are isolated by intervening clays and shales. Thus, the groundwater composition varies widely due to the effects of interbedded clays and shales. Ionic communication between waters is kept to a minimum by these clays and shales, although water may be free to move vertically from one aquifer to another.

Mineralogy. Reactive minerals in the rocks of the spoils and overburden include dolomite, calcite, kaolinite, siderite, gypsum, and pyrite.

Water Chemistry. Waters sampled span a range of high calcium, magnesium, and sulfate contents with high- to low-TDS and bicarbonate-enriched waters. Surface waters in contact with spoils are the most highly mineralized and enriched in magnesium relative to calcium. Spring waters are the least mineralized. Waters from coal beds and alluvium are intermediate between these two water types.

SECTION 8

DEVELOPMENT OF A PREDICTIVE METHOD

The overall objective of this ground-water mineralization study was to determine whether a correlation exists between overburden mineralogy and water quality in Western United States coal strip mines and, if so, to develop a method that can be used to predict water quality at other sites. The methods used to interpret the data, the interpretation of the data, and the results of the interpretation are discussed in this section. The successful predictive methods are presented in Section 9.

METHODS OF DATA INTERPRETATION

In this portion of the study, the various interrelationships beween geology, hydrogeology, mineralogy, and water chemistry are examined in detail. By determining the extent of influence that each of these parameters can exert on ground-water quality, a water quality system picture has emerged from the data. An understanding of this system will allow a mine operator to predict, before mining begins, whether any ground-water quality changes will occur due to the mining operation, and what the nature of these changes will be.

Factor Analysis

In order to collect together all the related or dependent major, minor, and trace-element compositional parameters as well as the mineralogy, factor analysis techniques were used. Factor analysis is, simply, a mathematical method of correlating a number of variables with one another and then assembling those that correlate into specific categories or factors. For example, measurement of the height and weight of a large number of people may indicate that a correlation exists between the two variables. It may then be said that height and weight are a size factor. A single variable factor, such as the length of hair, may not be correlative with any other variables. Fundamental to the procedure is the calculation of correlation coefficients of each pair of variables measured. This correlation coefficient array is then mathematically examined, and all those variables that correlate with one another are collected together in a group or factor. Each factor tends to be unrelated to every other factor. Factor analysis was used to determine interrelationships between:

- Whole rock mineralogy and bulk chemistry.
- Clay minerals and trace element content.
- Chemical and physical parameters of waters.
- Selected parameters representing rock and water compositions.

Geochemical Calculations

The objective of this phase of the program was to provide a thermodynamically sound model for the interaction of ground water with rocks in mined areas. It is of the utmost importance that the chemical mechanism of interaction between rock and water be understood on a fundamental thermodynamic level before any statements about water quality are made. The data reduction phase was designed to provide baseline information on the thermodynamic state of the waters in contact with rock in the mined areas.

Reduction of water analyses was accomplished using the Fortran version of the U. S. Geological Survey's computer program "WATEQ" by Plummer, Jones, and Truesdell (35). This program calculates the equilibrium distribution of inorganic aqueous species in waters using a laboratory analysis of major and minor ions, and field measurements of temperature, pH, and oxidation-reduction potential.

In order to calculate the equilibrium state of the water samples, certain basic information must be available. This includes a set of possible aqueous species, their charges and gram-formula weights, and a set of possible reactions with equilibrium constants and free energy changes. "WATEQ" considers a total of 115 possible aqueous species and 193 possible reactions which involve the more common rock-forming minerals. The basic calculation is carried out in the following way.

> The water analysis is read in and ion concentrations are converted to molality. All values of equilibrium constants are recalculated to the temperature of interest using the van't Hoff equation, unless experimental data are available. A cation-anion balance is calculated. If the charge balance error is greater than 30%, calculation is terminated at this point. If the charge balance is satisfactory, oxidation-reduction data, including electron activity and Eh, are calculated. As a final preparatory calculation, the Debye-Hückel solvent constants are corrected for temperature.
>
> During the next phase of computation, single-ion activity coefficients are calculated using the Davies equation or the Debye-Hückel approximation. With these, the activities

of all possible aqueous species can then be computed. The distribution of these species is then calculated by means of a chemical model (36), which uses analytical concentrations, experimental solution equilibrium constants, mass balance equations, and the measured pH. This distribution is presented in the form of a table which contains the concentrations, in mg/l and molality, the activities, and the activity coefficients of all possible aqueous species.

In the final phase of the calculation, saturation data are computed. Ion activity products for all possible reactions are calculated and compared with the temperature-corrected equilibrium constants. This information is, again, presented in a table containing ion activity products, equilibrium constants, the ratio of these two values, and the logarithms of all of these, and also the ΔG of reaction. In this way, one can readily determine which reactions are controlling the water composition, and which reactions are impossible under equilibrium conditions.

The results of the computations described above can be applied to the rock-water system in two ways. First, examination of the reaction status for various minerals can suggest the origin of dissolved constituents, and assist in the prediction of the chemical effects of mining on ground-water quality. This is accomplished by examining the saturation state of the water with respect to the minerals contained in surrounding rock, as well as with respect to aqueous species which have exceeded their saturation limit. In this way, one can construct a model of mass transfer of an element in a host rock, to the water, and back to the surrounding rock again, in a different form when saturation is reached.

In addition to providing an equilibrium picture of the water as it exists presently, "WATEQ" can be used to predict a change in water quality which might occur should the equilibrium state be altered. By changing parameters such as temperature, pH, or dissolved oxygen content the solubilities of many phases can be drastically altered. A fairly accurate picture of the consequences of equilibrium displacement can be achieved by calculation alone using this method.

Graphical Representation of Waters

Graphical representation of water compositions provides a quick and easy method for classification of water types. Groupings or trends are easily seen and parameters which provide distinctions between waters can be singled out. Four methods of graphical representation were used during the data interpretation phase of this project. These were triangular representations, trilinear diagrams, Stiff diagrams, and "vector" diagrams.

Triangular or Three-Component Diagrams --

This technique involved the selection of a typical surface water, an artesian water, and an unmineralized water. All other waters were assumed to be composed of a mixture of these three and were plotted on a standard triangular diagram. Although useful at the Energy Fuels and Edna Mines, it was considered too cumbersome to prepare for the other mines, and the selection of the end-member waters was somewhat subjective.

Trilinear Plots --

Trilinear plots were prepared in this study, but were not effective for data comparison. A complete description of the construction and use of trilinear plots can be found in Hem (37).

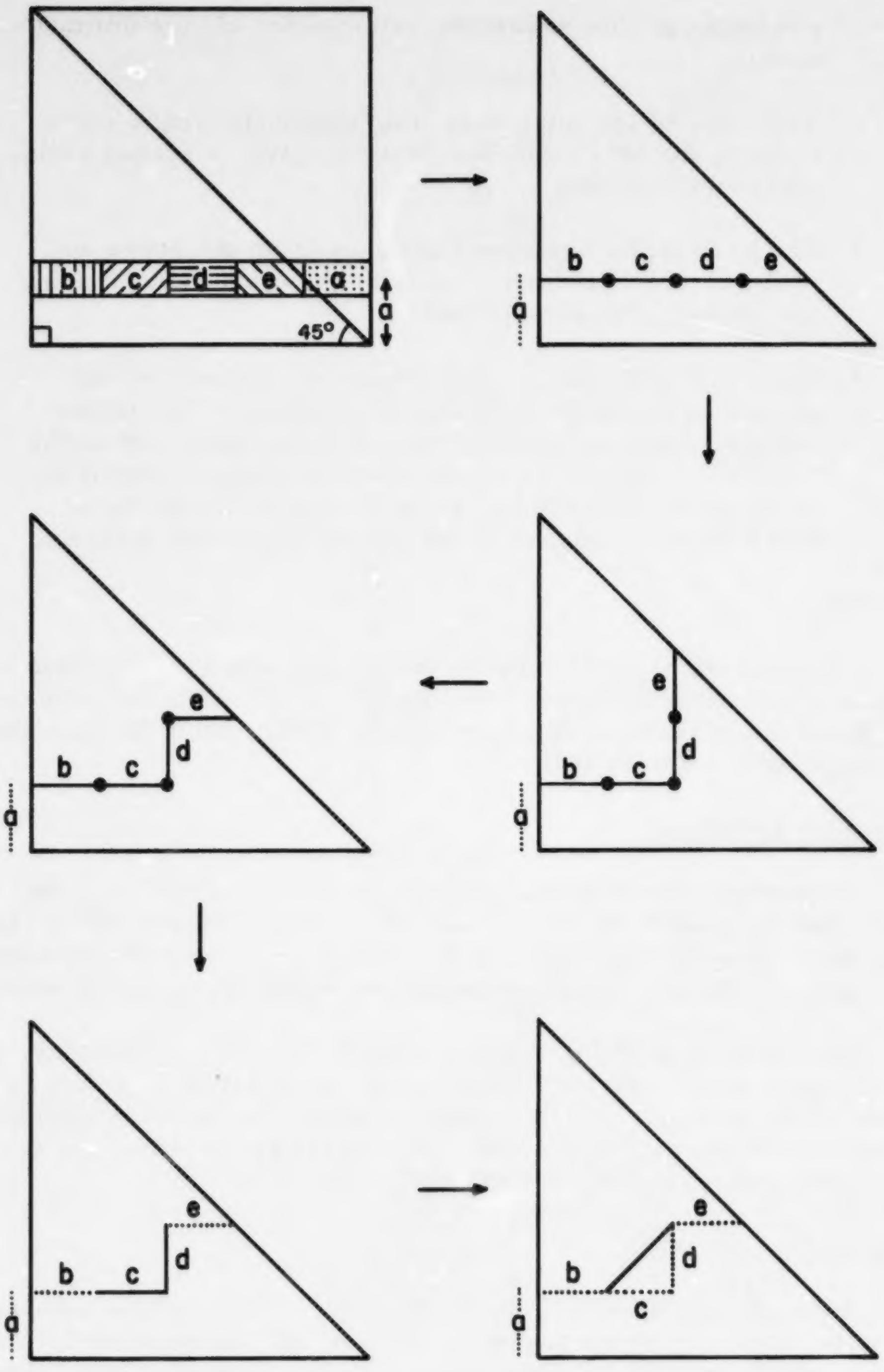
Stiff Diagrams --

This technique enables six components, generally three cations and three anions, to be plotted as a six-sided figure (38). The shape and size of the resulting figure allows for the comparison of water analyses--the shape reflecting composition and the size indicating the degree of dilution of the water. The principal objection to this technique is that each water analysis is plotted as an individual figure typically resulting in a large number of figures which can be unwieldy.

Vector Diagrams --

The approach found to be the most satisfactory for this study is that of plotting five components on what is usually referred to as a "vector" diagram. The name is somewhat misleading in that the line plotted is not a true vector. This method of representing multicomponent systems is of Russian origin and introduced to the English-speaking world by Korzhinski (39). Subsequently, it was used to illustrate petrologic relationships Hounslow (4). Thus, percentage composition, typically represented as a bar graph, can be plotted as a line on a right isosceles triangle, each side of which represents 100% of the composition. Using this system, three components are represented by a point, four components by a line parallel to one side of the triangle, and five components by an inclined line, or "vector." A detailed derivation of the five-component vector diagram is given in Figure 58. Some aspects of these diagrams may not be immediately obvious:

- The slope of the "vector" representing the composition gives a ratio of two of the components; for the diagrams



b
c
d
e
a
a
45°
b
c
d
e
a
e
d
b
c
a
b
c
d
e
a
e
d
b
c
a
e
b
d
c
a
e
b
d
c
a

Figure 58. Derivation of a five-component vector diagram from a five-component bar graph.

presented in this report the ratio is that of calcium:magnesium.

- The slope of the imaginary line joining the origin (zero-zero) to the lower end of a "vector" gives a second ratio, sulfate:bicarbonate.

- The vertical or horizontal distance from the upper end of the vector to the hypotenuse of the triangle represents the amount of sodium present.

- All water analyses for this study were calculated and plotted on the basis of 50 meq/l of cation. The anions, sulfate, and bicarbonate, which are the lower end of the "vectors," should lie on the 50-50 hypotenuse line if the anion-cation balance is correct. Any deviation from this line is a measure of the inaccuracy of the analysis.

GEOLOGY

The geological environments at the mine sites investigated varied widely in overburden lithology, stratigraphic continuity, and structure. The effect that each of these parameters had on water quality is described under their respective headings below.

Overburden Lithology

In general, overburden at all mines consisted of sandstone, siltstones, shales, mudstone, coals, and occasionally limestones. The sandstones and siltstones were frequently calcareous and the shales usually carbonaceous. Coals and sandstones often contained pyrite and gypsum.

Examination of the data shows that differences in lithology, from mine to mine, other than mineralogy, had relatively little effect on the correlation of the quality of ground water from the mines. The effects of lithology and to a lesser extent climate, are masked by the effects of the groundwater composition entering the system.

Stratigraphic Continuity

Lateral discontinuity or lenticularity of strata is characteristic of most mine sites. At some mines lateral continuities persisted for only a few feet, whereas at other mines beds could be correlated over several miles.

Examination of the data shows that the degree of lenticularity of strata in the overburden cannot be correlated with any ground-water quality changes. It should be noted, however, that lensing of shale beds into surrounding sandstones or siltstones can give rise to deposits of soluble salts at the shale-sandstone contact. Should this be the case, spoiling of overburden will result in the leaching of these soluble salts by water in the spoils.

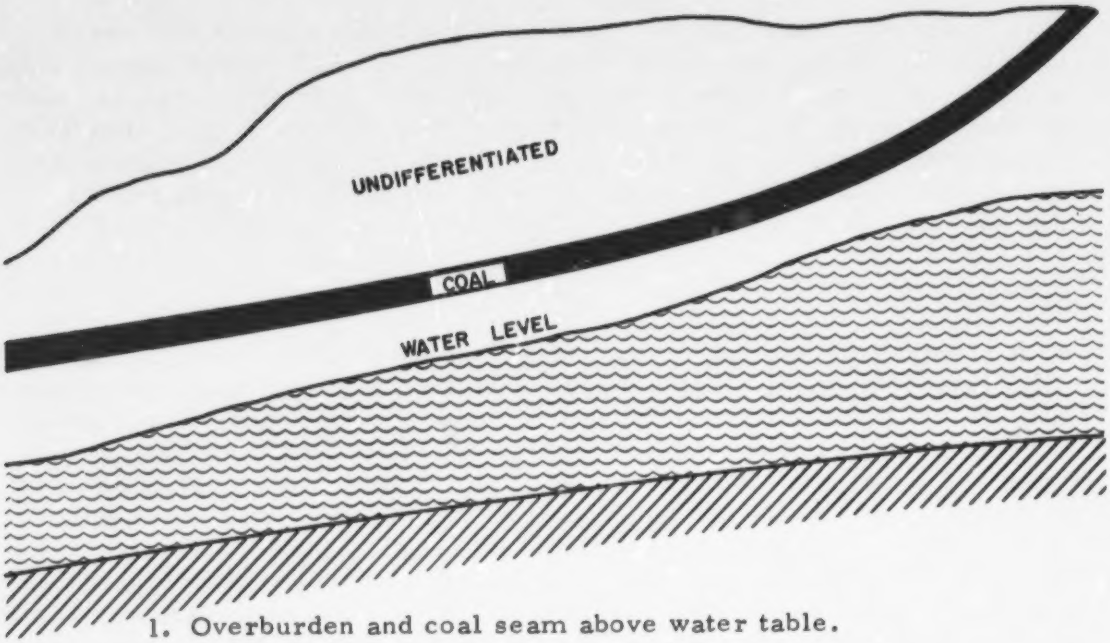
Structure

Structural geology at the mine sites varied from nearly horizontal, undeformed strata, to steeply dipping folded strata. Two major structural features, found to affect ground-water flow at the mine sites investigated, were folding and faulting. At mine sites where the beds were nearly flat-lying and undeformed, ground-water flow directions were readily determined. At mine sites where strata were deformed, ground-water flow directions were difficult to ascertain, and the source of waters recharging the mine area was questionable. The presence of faults at several mines also complicated the ground-water picture by acting as barriers or channels to ground-water flow.

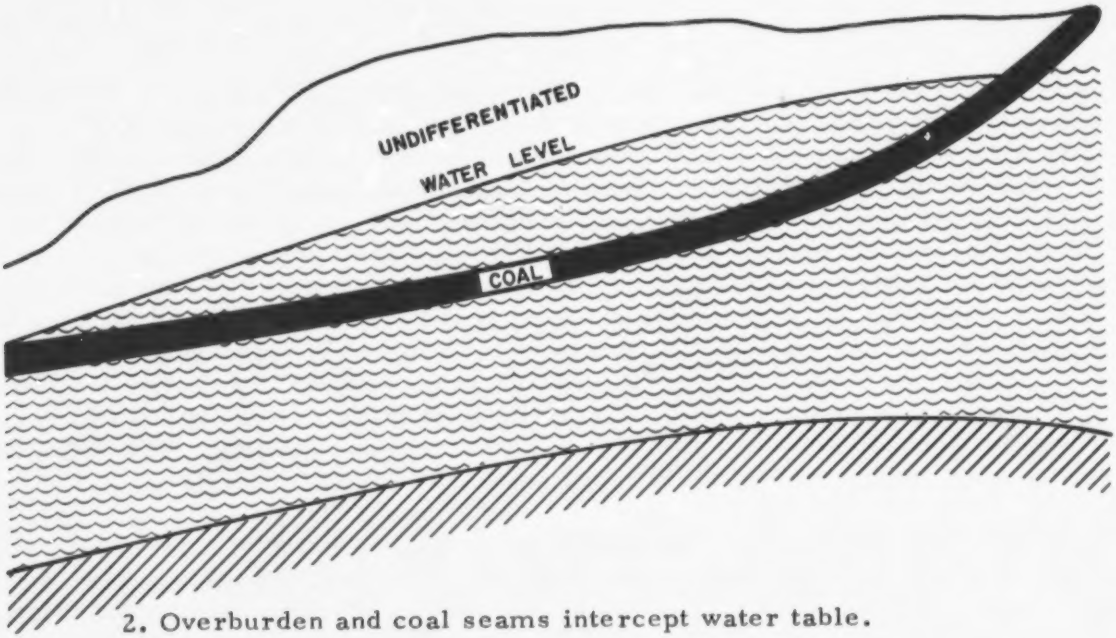
HYDROGEOLOGY

In the course of this study, five ground-water overburden relationships were found. Combinations of these, or other entirely different relationships no doubt exist in other areas. The five ground-water overburden relationships are: (1) Overburden and coal seams are above the water table; (2) Overburden and coal seams intercept the water table or overburden contains a confined aquifer above the coal; and (3) Overburden and coal occur above a confined aquifer (Figure 59). Combinations of these conditions usually exist where more than one coal seam is being mined and the interburden materials are significantly different, mineralogically, from materials above the first coal to be stripped. In addition to these three, two other relationships can be commented on as a result of this study: (4) Overburden is within an unconfined aquifer, and the coal seam is below; and (5) Overburden that contains a confined aquifer is above the coal.

Where the overburden and the coal seam occur above the water table, relationship number one, very little difference was noted between the composition of waters that passed through the undisturbed overburden and through the homogenized, spoiled overburden (assuming that recharge is primarily a result of infiltration of precipitation on the proposed mine area). This is true because the waters passing through undisturbed overburden came in contact with the same minerals before mining as after mining. The TDS of spoil waters was greater as a result of both evaporation and increased surface area of the rocks. This same conclusion can be applied to relationship

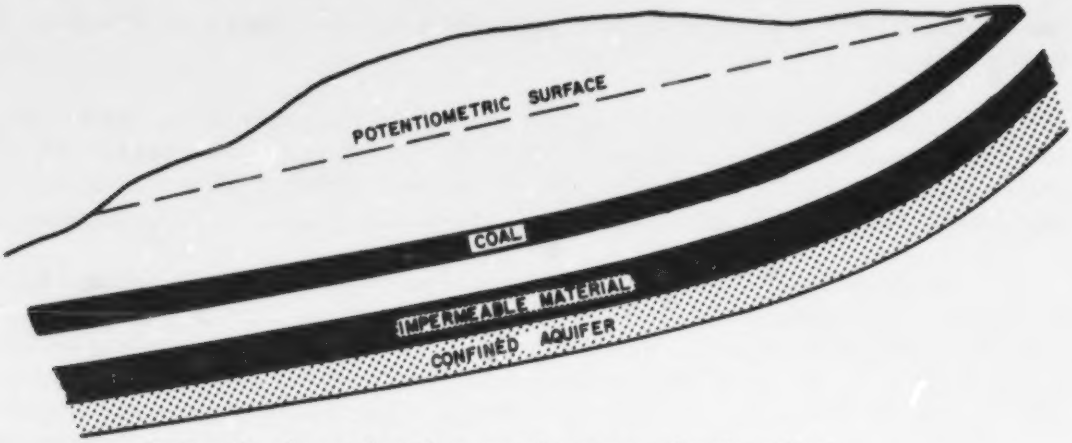

UNDIFFERENTIATED
COAL
WATER LEVEL

1. Overburden and coal seam above water table.

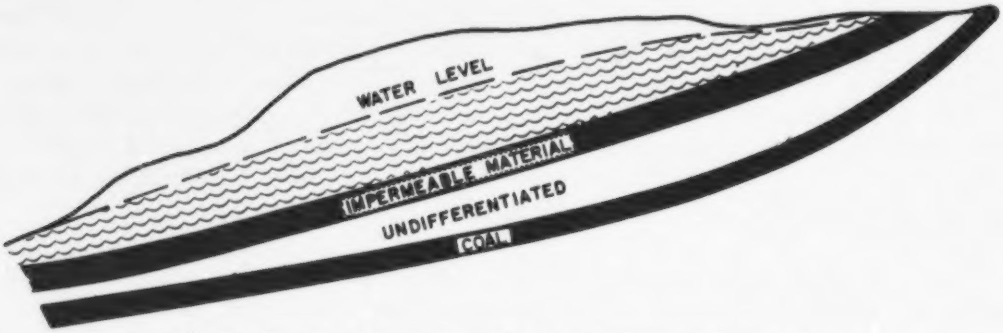

UNDIFFERENTIATED
WATER LEVEL
COAL

2. Overburden and coal seams intercept water table.

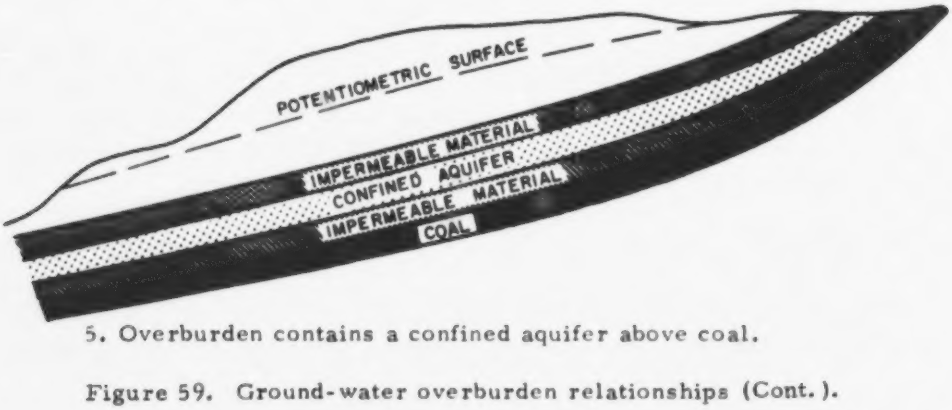
Figure 59. Ground-water overburden relationships.


POTENTIOMETRIC SURFACE
COAL
IMPERMEABLE MATERIAL
CONFINED AQUIFER

3. Overburden and coal occur above a confined aquifer.


WATER LEVEL
IMPERMEABLE MATERIAL
UNDIFFERENTIATED
COAL

4. Overburden within an unconfined aquifer; coal below.


POTENTIOMETRIC SURFACE
IMPERMEABLE MATERIAL
CONFINED AQUIFER
IMPERMEABLE MATERIAL
COAL

5. Overburden contains a confined aquifer above coal.

Figure 59. Ground-water overburden relationships (Cont.).

number two, where the overburden and coal seam are within or intercept the water table.

Where the coal and overburden materials lie above a confined aquifer, relationship number three, no changes were noted. No intermixing of water from this aquifer with minerals disturbed during mining can occur and, thus, the lack of any change in ground-water quality is to be expected.

When the coal occurs below an unconfined aquifer, relationship number four, some noticeable differences in water quality between the undisturbed and the disturbed overburden can be anticipated. This is because the impermeable layer above the coal generally consists of shales that contain highly soluble minerals once they are disaggregated. In some cases, where these shales contain abundant clays, this difference could be of a beneficial nature. The clays can adsorb a considerable amount of normally deleterious heavy and trace metals.

The greatest distinction that is likely to occur between waters from undisturbed overburden and homogenized spoils will be where the overburden contains a confined aquifer above the coal, relationship number five. In this instance, the water from the confined aquifer will be mixing with an entirely different suite of minerals after stripping than it had when in the confined state. This is especially true if the confined aquifer consists of relatively inert minerals such as are found in a clean sandstone.

In addition to the ground-water configurational changes which will occur upon spoiling, certain physical characteristics will also be drastically changed. The most obvious of these are porosity, permeability, and surface area available for reaction. The amount of mineral matter dissolved from the spoil material depends upon the volume of water flowing through and the residence time, or flow rate, of this water.

MINERALOGY

An examination of the data presented in the previous sections shows that certain minerals appear consistently in the rocks of the overburden and subsequent spoils. The objective of this portion of the study is to investigate the interaction of ground water with these minerals. When water contacts solid material, three reactions are possible:

- Solid material may be dissolved.
- Ions already in solution may be exchanged for other ions bonded to the solid material.

- Ions in solution may be precipitated and removed from the water, or travel with it as a suspended solid.

Further, some reactions that are thermodynamically possible, albeit slow, may be catalyzed and rendered much faster by microbial interaction. Sulfate reduction and sulfide oxidation are two well-documented examples.

The rocks typically encountered as coal seam overburden were sandstones, siltstones, shales, and limestones. Both the sandstones and siltstones were composed essentially of quartz and feldspars, and both were relatively insoluble in water -- at least within the time period under consideration. Shales, composed predominantly of clay minerals, were basically hydrous aluminum silicates that may contain considerable quantities of other elements. Because of their unique crystal structure, clays may exchange these elements for other elements by an ion-exchange process in a solution with which they are in contact. Another mineral commonly occurring in the shales was gypsum ($CaSO_4 \cdot 2H_2O$), which is significantly soluble in water. Limestone consists of the carbonate minerals calcite ($CaCO_3$), dolomite $[CaMg(CO_3)_2]$ and/or siderite ($FeCO_3$), and the solubilities of these minerals depends on pH, carbon dioxide content of the water, and temperature.

Minerals that may occur as nonessential or accessory minerals in any of the above rock types are the sulfide minerals, which are the source of acid waters frequently causing degradation of ground water in the eastern coal mining areas. Pyrite (FeS_2) is the most common of these sulfides. Oxidation of pyrite releases sulfuric acid (H_2SO_4) which, in an unbuffered system, causes a drastic decrease in pH. Carbonate minerals are important in this regard because they can act as a neutralizer in acid water environments.

The chemical elements occurring in rocks that are not essential to the crystal structures of the minerals present are known as trace elements. Their presence cannot be inferred from a mineralogical analysis and, thus, requires chemical analysis for detection. Research in recent years has shown that the presence of even trace amounts of some metals, such as mercury, has a serious effect on water quality. Detecting the presence and determining the origin of these trace metals is, therefore, an important aspect of this study. Clay minerals are also important in that they can act as chemical sponges, exchanging and adsorbing undesirable heavy metals and releasing less toxic ones.

Calcite - $CaCO_3$

Calcite was found as a matrix constituent of the clastic sedimentary rocks and as the principal component of limestones. It is identified in hand samples by its effervescence with cold, dilute hydrochloric acid. X-ray diffraction also allows its detection as well as a semiquantitative estimate of the amount present.

Calcite is readily soluble in dilute acids. It dissolves in the carbonic acid produced during the normal atmospheric weathering cycle,

$$CaCO_3 + CO_2 + H_2O \rightleftarrows Ca^{++} + 2HCO_3^-,$$

and in the sulfuric acid produced by the oxidation of pyrite which occurs in spoil piles,

$$CaCO_3 + H_2SO_4 \rightleftarrows Ca^{++} + SO_4^= + H_2CO_3.$$

The end result of the dissolution of calcite is neutralization of these acids and the production of calcium and bicarbonate. X-ray diffraction data show that calcite was present in the overburden and in the spoils at all mines. Geochemical calculations show that it was at or near equilibrium in all ground and surface waters except those with sufficiently low pH's to preclude the existence of bicarbonate.

Factor analysis indicates that the only other element associated or related to calcite was sodium. The association of calcite with sodium, coupled with the lack of correlation with plagioclase, cannot be explained.

Dolomite - $CaMg(CO_3)_2$

Dolomite is the principal carbonate constituent of most of the rocks examined and was detected by x-ray diffraction in all cases.

Solution of dolomite may be accomplished by dilute acids:

(carbonic) $CaMg(CO_3)_2 + CO_2 + H_2O \rightleftarrows Ca^{++} + Mg^{++} + 2HCO_3^-$, or

(sulfuric) $CaMg(CO_3)_2 + H_2SO_4 \rightleftarrows Ca^{++} + Mg^{++} + SO_4 + 2HCO_3$.

The end results of the solution of dolomite is the neutralization of acid and the production of calcium, magnesium, and bicarbonate. In the case of dissolution by sulfuric acid, calcium, magnesium, and sulfate may recombine and eventually lead to the precipitation of one or more of the hydrated sulfate minerals.

X-ray diffraction data show that dolomite was present in the overburden and spoils at all mines. Geochemical calculations show that waters from most mines were close to equilibrium with respect to dolomite. Waters at several mines were frequently oversaturated with respect to dolomite, but secondary precipitation of this mineral is unlikely because reaction kinetics are too slow to allow this to take place.

Factor analysis revealed a strong correlation of the element strontium with dolomite.

Siderite - $FeCO_3$

Siderite generally is associated with coal or other organic matter. It was identified by x-ray diffraction, but was also discernible in some samples by visual examination. Siderite is generally coarse grained with a distinctive cleavage and a prominant brown color. The mineral effervesces only with hot dilute hydrochloric acid.

Siderite precipitates when a solution containing abundant ferrous iron mixes with a solution containing carbonate or bicarbonate, or when a solution containing all these ions either evaporates or becomes alkaline. It is not a common sedimentary mineral because most of the iron liberated by weathering is immediately oxidized to ferric oxide. The amount of ferrous iron in surface waters is, therefore, vanishingly small. Under reducing conditions, however, such as with waters associated with coal seams, siderite may be precipitated in large quantities. Under surface conditions, dependent on both pH and the presence of free oxygen, siderite is dissolved by the reaction:

$$2FeCO_3 + \tfrac{1}{2}O_2 + 2H_2O \rightleftarrows Fe_2O_3 + 2H_2CO_3.$$

The net result of this reaction is the production of carbonic acid and iron which will usually reprecipitate as amorphous ferric hydroxide.

X-ray diffraction shows that small amounts of siderite were present at Energy Fuels, McKinley, Medicine Bow, Kemmerer, and Colstrip Mines. These occurrences were generally associated with coal beds. Siderite was not detected in samples from the Edna or Rosebud Mines.

Geochemical calculations show that all ground and surface waters from all mines were undersaturated with respect to siderite. Eh-pH conditions in all waters were such that siderite is unstable under the present geochemical regime.

Factor analysis revealed the other elements with siderite to be manganese and magnesium.

Gypsum - $CaSO_4 \cdot 2H_2O$

Gypsum is a commonly occurring constituent of marine shales and a not uncommon constituent of the hardpan or caliche layer in Western soils.

Identification of gypsum was accomplished by x-ray diffraction and/or by using the mercuric nitrate stain to identify sulfate and a titan yellow stain to test for magnesium; if the latter was negative and the former positive gypsum was assumed to be present. Gypsum is one of the more readily soluble minerals encountered, its solubility varying from 2,500 to 3,000 mg/l depending on the ionic strength and temperature of the solution.

Gypsum precipitates readily from solutions produced by the oxidation of pyrite coupled with the dissolution of limestone:

(oxidation of pyrite) $2FeS_2 + 15/2O_2 + 4H_2O \rightleftarrows Fe_2O_3 + 4H_2SO_4$

(dissolution of limestone) $H_2SO_4 + CaCO_3 \rightleftarrows Ca^{++} + SO_4^{=} + H_2CO_3$

(precipitation of gypsum) $Ca^{++} + SO_4^{=} + 2H_2O \rightleftarrows CaSO_4 \cdot 2H_2O$

This reaction sequence occurs readily in spoil piles.

X-ray diffraction showed that gypsum was a ubiquitous constituent of spoil and overburden rocks at all mines, generally occurring in highest concentrations at or near the surface when evaporation concentration of calcium sulfate-rich waters can occur.

Geochemical calculations show that gypsum was at or near equilibrium in all surface waters, and in ground waters derived from shales and coals.

Starkeyite - $MgSO_4 \cdot 4H_2O$

Magnesium sulfates exist with varying degrees of hydration from $MgSO_4 \cdot H_2O$--kieserite, which is relatively common in normal evaporites, to $MgSO_4 \cdot 7H_2O$--epsomite, a rarer constituent of marine evaporites. The other members of the series are quite rare and have generally been reported as efflorescences on kieserite. In this study, magnesium sulfate occurred as surface encrustations and bedding plane fillings at many mines.

One sample of a surface encrustation was x-rayed and found to be starkeyite; however, most other occurrences were identified on the basis of positive stain tests for magnesium and sulfate and, thus, the degree of hydration was not obtained.

The extreme solubility of magnesium sulfate indicates that it is most likely secondary in origin and probably the result of concentration by evaporation. This possible origin is of some considerable interest because it is a product of spoil and overburden leaching and also because it was the only mineral reported that contains magnesium as the only cation. Sources of magnesium are dolomite and clay minerals.

A solution enriched in magnesium sulfate is produced by the dissolution of dolomite in dilute sulfuric acid, followed by evaporation and precipitation of gypsum when the solubility of this mineral is exceeded. A second mechanism for the concentration of magnesium sulfate involves the interaction of a solution containing various metal sulfates and clay minerals by cation exchange reactions, the metals being absorbed and the magnesium liberated.

No geochemical calculations were made due to the lack of free-energy data for any of the magnesium sulfate species.

Pyrite - FeS_2

Pyrite is the most widespread and most abundant of sulfide minerals. It is a common constituent of sedimentary rocks where it generally occurs as disseminated crystals or in concretionary forms. Further, it is the principal sulfide present in nonlignitic coal seams. Identification was based on x-ray diffraction and the observation of bright-yellow metallic grains.

The oxidation and dissolution of pyrite with the liberation of sulfuric acid is responsible for the acid mine drainage problem of many coal mines in the Eastern United States.

The reaction,

$$2FeS_2 + 15/2O_2 + 4H_2O \rightleftarrows Fe_2O_3 + 4H_2SO_4,$$

is reported to be catalyzed by microbial action.

With limited amounts of pyrite and excess limestone, this acid is neutralized and generally gypsum is deposited. Iron is generally precipitated as amorphous ferric hydroxide.

X-ray diffraction and microscopic examination showed that small amounts of pyrite were ubiquitous in the coals and, frequently, in the overburden from many mines.

Feldspar

Feldspars rank among the most abundant minerals of the earth's crust. They are extremely widespread constituents of igneous, metamorphic, and clastic sedimentary rocks, and were major constituents of the rocks at all mine sites. The common forms are:

$KAlSi_3O_8$ - orthoclase or microcline (potash feldspar)

$$\left.\begin{array}{l} NaAlSi_3O_8 \text{ - albite} \\ CaAl_2Si_2O_8 \text{ - anorthite} \end{array}\right\} \text{(plagioclase series)}$$

Identification and differentiation of feldspar in this study were accomplished by x-ray diffraction.

Feldspars, being silicate minerals, are relatively insoluble in water, although under long-term weathering conditions they are generally regarded as a major source of clay minerals. Some sodium and potassium present in ground water may be the result of feldspar dissolution, but it is unlikely that these minerals contribute much to waters percolating through spoil piles especially because of the short time frame being considered.

Geochemical calculations showed that all waters were undersaturated with respect to feldspars. Under the existing geochemical conditions, the feldspars were unstable.

Factor analysis revealed a correlation between potash feldspar and lead.

Quartz - SiO_2

Quartz is the most common and ubiquitous of all minerals. Positive identification of quartz was accomplished by x-ray diffraction.

Because of its relative insolubility, quartz must be considered to be a stable constituent of spoil piles, adding only 10 to 20 mg/l of SiO_2 to the water.

Clay Minerals

Clay minerals are extremely fine-grained hydrous silicates, principally of aluminum or magnesium. The four important clay groups are those containing kaolinite, illite, montmorillonite, and vermiculite. These have characteristic basal spacings of 7Å, 10Å, 15Å, and 14.5Å, respectively, which are readily measured by x-ray diffraction techniques.

Clays of the montmorillonite and vermiculite groups can adsorb certain organic liquids between their structural layers resulting in an increase in their basal spacings. This increase can be measured using x-ray diffraction and, if the organic material is known, the clay may be identified.

Clay minerals are formed primarily by the weathering of other aluminum silicates in a slow and complicated hydrolysis process. The nature of the clay mineral formed depends upon the environment of weathering. The most important factors in the formation of clay minerals are:

- Mineral composition of the rock.
- Chemical composition of the water.
- The rate of passage of the water through the rocks.

Clay formed in one environment might slowly change in character if the environment changes.

All solid nonmolecular substances have unsatisfied bonds at their surfaces. The finer grained the material, the higher the surface-to-volume ratio and the greater the surface charge. Clays are fine grained and would therefore be expected to have a high surface charge. In addition, a common characteristic of clays is that substitutions of one ion for another ion having a different valence may occur--a phenomenon which would dramatically increase this surface charge, unless such substitutions are appropriately coupled with one another. Common substitutions are:

- Al^{+3} for Si^{+4}
- Fe^{+2} or Mg^{+2} for Al^{+3}
- OH^- for O^{-2}.

This net charge on the layers leads to the adsorption of cations from solution, the adsorbed ions being replaced by others when the concentration or pH of the solution changes. The sum of these exchangeable cations is called the cation exchange capacity (CEC).

Montmorillonite and vermiculite have a much higher cation exchange capacity than illite (mica) or kaolinite. Consequently, their presence may be of considerable importance in that various toxic heavy-metal trace elements released during weathering may be collected by these clays. Furthermore, once adsorbed, these heavy metal cations tend to resist further exchange.

Anion exchange is also possible in clay minerals. Exchange occurs largely with exposed hydroxyl groups on the edges of clay flakes; almost none occurs at basal plane surfaces.

If the pH of the soil solution rises to above 10.0 or drops to below 4.0, clay exchangers are destroyed and minerals become soluble in the aqueous solution with subsequent liberation of aluminum and silica.

Major Clay Species

Kaolinite, $Al_4[Si_4O_{10}](OH)_8$, is the most common of the clay minerals and generally results from the alteration of feldspars in silicic rocks by acid solutions and under conditions of good drainage. It was the predominant clay mineral at all mine sites.

Illite, $K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}](OH)_4$, is a major constituent of many shales and mudstones. It is formed by the alteration of micas and feldspars under alkaline conditions. High concentrations of aluminum and potassium favor the formation of illite.

Montmorillonite, $(\frac{1}{2}Ca,Na)_{0.7}(Al,Mg,Fe_4[Si,Al)_8O_{22}](OH)_4 \cdot nH_2O$, is the principal constituent of bentonite clay deposits as well as being common in soils and shales. It results from the alteration of silica-poor rocks or volcanic material by alkaline solutions and its formation is favored by the availability of magnesium and calcium coupled with a deficiency of K.

Vermiculite, $(Mg,Ca)_{0.7}(Mg,Fe^{+3},Al)_6(Al,Si)_8)_{20}(OH)_4 \cdot 8H_2O$ is widespread in some soils and is usually the result of the alteration of existing biotite mica. It also forms by the alteration of volcanic material, chlorite, and hornblende. It is rare in marine sediments because of the amount of potassium in seawater. Vermiculite is similar to montmorillonite in that it has a net negative charge on the mineral, but differs in that this charge results from the one-for-one substitution of aluminum and silicon. Factor analysis indicates that vermiculite is forming at the expense of mica in this rock.

WATER CHEMISTRY

Water analyses from all mines were examined using graphical representation and geochemical calculations, although factor analysis was used only at the Energy Fuels and Edna Mines. The results of the data reduction are presented below, followed by a summary of the chemical reactions important to water chemistry.

Graphical Representation of Waters

A complication in the interpretation of water chemistry data is the effect of dilution. Thus, it is necessary to consider element ratios on the one hand and the total dissolved solid content on the other.

The analytical results of the water chemistry from both the Energy Fuels Mine and the Edna Mine were calculated on the basis of 100 milliequivalents (meq) of cations per liter (see Table 20). Cations were chosen because the accuracy of their determination was higher than that of the anions.

TABLE 20. ANALYSES CALCULATED TO 100 MILLIEQUIVALENTS PER LITER CATIONS

	Sample No.	Ca	Mg	Na K*	Surface Artesian Ratio	Cl	SO_4	CO_3 HCO_3	$\frac{TDS_c}{TDS_m}$ Ratio	TDS	
										Calc.	Meas.
Energy Fuels Mine	D-6	5	5	90	0.10	7	39	58	1.01	795	800
	CD-7	40	35	25	0.58	26	835	132*	0.18	1,753	318
	CD-8	22	19	59	0.42	3	18	86	0.31	1,433	446
	D-9	2	1	97	0	2	17	86*	1.44	596	860
	D-14	24	12	64	0.44	3	64	46	0.74	1,473	1,086
	S-6	52	37	11	0.88	2	66	27	0.67	2,351	1,568
	S-9	27	31	42	0.63	2	59	32	0.92	1,852	1,710
	S-10	16	13	71	0.28	2	29	75	0.69	1,154	798
	SF	54	41	4	1.00	1	81	13	0.96	2,590	2,475
	ST-1	34	50	16	0.92	4	86	24	1.00	2,430	2,444
	P-1	28	48	24	0.70	8	22	64*	0.21	1,992	416
	P-2	61	35	4	1.00	1	100	15	0.98	2,590	2,546
	P-3	61	35	4	1.00	1	103	7	1.18	2,590	3,058
	SL-3	46	33	21	0.83	4	78	10	1.33	2,251	3,000
	SL-4	30	27	43	0.60	4	80	10	1.39	1,792	2,483
Edna Mine	D-5	61	24	5	0.94	2	72	30	0.63	2,470	1,550
	S-7	54	36	10	0.93	5	22	79	0.05	2,450	124
	S-8	63	28	9	1.00	5	368	34	0.23	2,590	608
	SP-1	58	40	2	1.00	1	99	8	0.96	2,590	2,480
	SP-2	61	37	2	1.00	1	97	12	0.95	2,590	2,456
	SP-3	61	37	2	1.00	1	84	7	1.07	2,590	2,782
	SP-4	63	34	3	1.00	1	94	7	1.08	2,590	2,810
	P-1	65	32	3	1.00	1	12	5	1.06	2,590	2,740
	P-2	65	31	4	1.00	1	104	3	0.86	2,590	2,226
	P-3	61	36	3	1.00	1	76	5	0.99	2,590	2,574
	SL-3	58	39	3	1.00	1	102	6	1.13	2,590	2,920
	SL-10	62	27	11	1.00	4	100	12	1.10	2,590	2,850
	SL-12	12	18	70	0.30	1	86	17	2.10	1,194	5,440

* Maximum K is 2 meq/l.

** Some CO_3 present.

The cations present in significant amounts are calcium, magnesium, sodium, and to a much lesser extent, potassium. Similarly significant anions are sulfate, bicarbonate, carbonate, and chlorine.

Inspection of these recalculated data (Table 21) revealed a remarkable similarity in the analyses of waters from Springs 1 to 4, and from Ponds 1 to 3 from the Edna Mine and Ponds 2 and 3 from the Energy Fuels Mine. These samples were high in calcium, magnesium, and sulfate and low in sodium and bicarbonate. Examination of the remaining analyses showed that Sample D-9 contained the lowest amounts of calcium, magnesium, and sulfate as well as the highest sodium content. Further, omitting the results of Sample CD-7 which are obviously in error, D-9 ranked third in bicarbonate content.

It is seen that the two waters have chemical compositions which are diametrically opposed to one another. Type 1, high in sodium and bicarbonate, were deep water samples. A Type 2 water, high in calcium, magnesium, and sulfate, is characteristic of waters which have been in contact with spoils of the springs, ponds, and streams.

Assuming the presence of two waters with extreme compositions described above, an attempt was made to explain the compositions of all the waters as mixtures of these two. This was successful, and the compositions of the two end-members were statistically refined. The composition of each sample relative to these end-members was determined graphically.

The next factor to be considered is that of dilution. The parameter selected to show this is the total dissolved solids (TDS). The surface water has a much higher TDS than the ground water. A theoretical TDS was calculated for each sample on the basis of a mixture of the two end-members discussed above. Although many of these values agreed closely with the determined values, in some cases the measured values were considerably less than the calculated values. This difference was presumed to be the result of dilution. The amount of dilution was determined using the actual and calculated TDS data, and the results are plotted on a triangular diagram (Figure 60). Sample S-7 from the Edna Mine plotted closest to the "unmineralized water" corner of the diagram. The water from this locality is from shallow alluvial aquifer water.

The lysimeter samples SL-3 and SL-4 from the Energy Fuels Mine, and samples SL-3, SL-10, and SL-12 from the Edna Mine, were recalculated on the basis of the above end-members. . Sample SL-12 was highly anomalous. The remaining samples had one characteristic in common--they were all more concentrated than the other samples described above. (See Methods of Investigation: Drilling).

TABLE 21. ALL ANALYSES RECALCULATED TO 100 MILLIEQUIVALENTS PER LITER CATIONS

	Ca	Mg	Na + K	Cl	SO_4	$CO_3 + HCO_3$	TDS
Hypothetical Waters and Sample Having Closest Composition							
Water 1 (Artesian)	-3	6	96	--	13	82	596
Energy Fuels Mine D-9	2	1	90	2	17	86	860
Water 2 (surface)	59	38	3	--	83	17	2,590
Edna Mine SP-4	63	34	3	1	94	7	2,810
Water 3 (alluvial)	54	36	10	--	22	79	124
Edna Mine S-7	54	36	10	5	22	79	124
Surface Waters Draining Areas of Known Rock Type							
Granite	83	12	4	3	11	44	43
Limestone	52	45	3	4	4	46	158
Gypsum	52	28	20	3	68	14	727
Shale	22	20	57	1	81	9	2,020

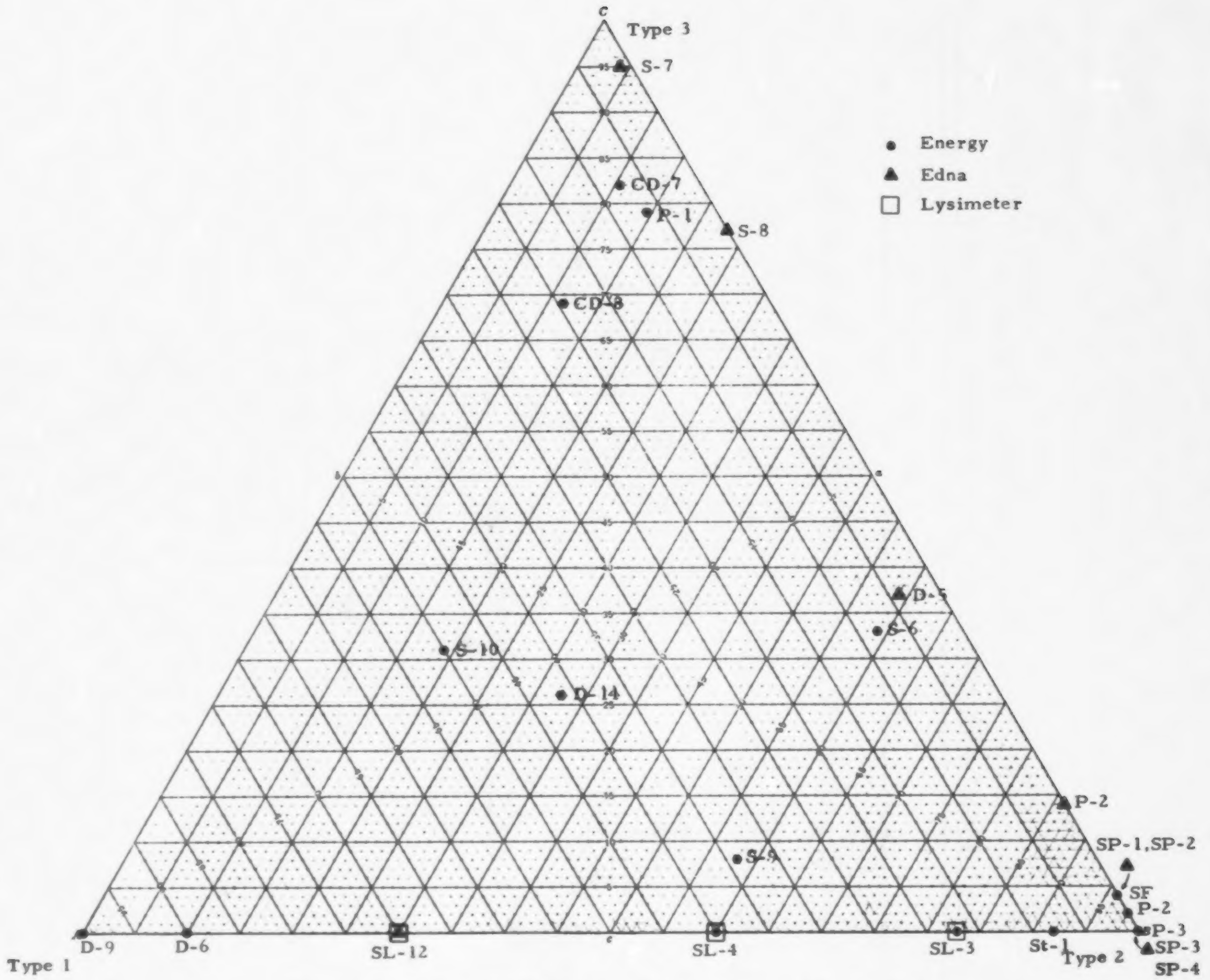


Figure 60. Water genesis in terms of three end-member types at the Energy Fuels and Edna Mines, Colorado.

The origin of these three water types is given below:

Water Type 1 ($Na-HCO_3$)--

The water most nearly representative of this end-member is that of Sample D-9 which is artesian in origin. The TDS content of this water type is approximately 600 mg/l. A preliminary examination of the literature suggests (at least for Western United States waters) that a sodic ground water usually contains sulfate as the predominant anion. On this basis, the sodium bicarbonate water is unusual. Also, it contains considerably less calcium and magnesium than is usually reported as occurring with the sodium. A possible explanation of the bicarbonate ground water is that it results from sulfate reduction. Where water and organic material are in contact, such as in coal seams, this reaction is catalyzed by anerobic bacteria. The reaction generally proposed is:

$$SO_4^{=} + CH_4 \rightleftarrows HS^- + HCO_3^- + H_2O$$

The sulfide produced by this reaction leads to the precipitation of iron and some heavy metals present in the original water.

Further, if calcium and magnesium were initially present in the water, these elements may have been absorbed by montmorillonite clay, releasing sodium into solution.

Water Type 2 ($Ca-Mg-SO_4$)

The samples representative of this water type are the four springs and three ponds from the Edna Mine, and two ponds from the Energy Fuels Mine. The water in these ponds either moved through the spoils material prior to emerging at the surface, or was otherwise in direct contact with spoils material.

Possible mechanisms for the production of Water Type 2 chemistry include:

- Leaching of the gypsum and starkeyite from the spoils piles. This would be the most likely mechanism assuming sufficient gypsum in the spoils.

- Bacterial or chemical decomposition of pyrite to sulfuric acid coupled with the solution of calcite and dolomite. This, again, is dependent upon the presence of pyrite.

- Bacterial oxidation of the organic sulfur in the coal and the reaction of the sulfuric acid so formed with calcite and dolomite. The coal does contain about 0.5% organic sulfur, and the near-neutral pH is optimal for most sulfur bacteria. The questionable points are, first, whether sufficient coal remains in the spoils to account for the sulfate content of the water, and second, whether sulfur oxidizing bacteria are present.

Water Type 3 (Ca-HCO_3 low TDS)--

The water most representative of this type is that of Sample S-7 from the Edna Mine, which is water from the shallow alluvial aquifer.

Vector Diagram Results

Vector diagrams of water from all mines are shown in Figures 61 through 68. Several conclusions can be drawn from a comparison of these eight diagrams:

1. Low-TDS waters were found in the following circumstances:

    a. Surface water above or outside a mine area.

    b. Shallow alluvial aquifers upstream from the mine.

    c. Ground water derived from confined sandstone aquifers.

    All these waters were of the sodium-calcium-bicarbonate type.

2. High-TDS waters were found in the following circumstances:

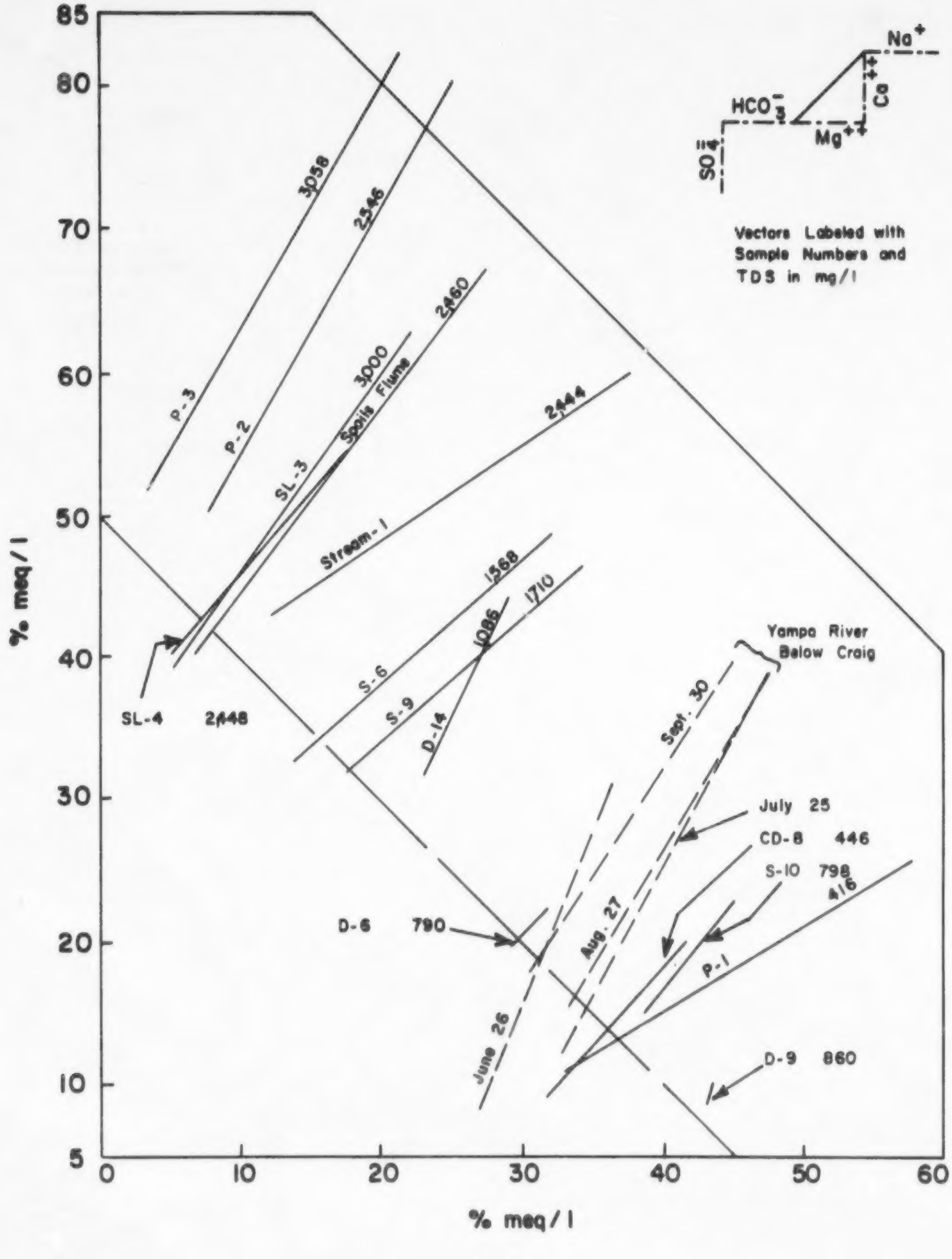


Figure 61. "Vector" diagram of water compositions. Energy Fuels Mine, Colorado. (Dashed lines from U. S. G. S. Water Resources Data for Colorado, 1975. Green River Basin. Analyses appear in Appendix Table C-9.)

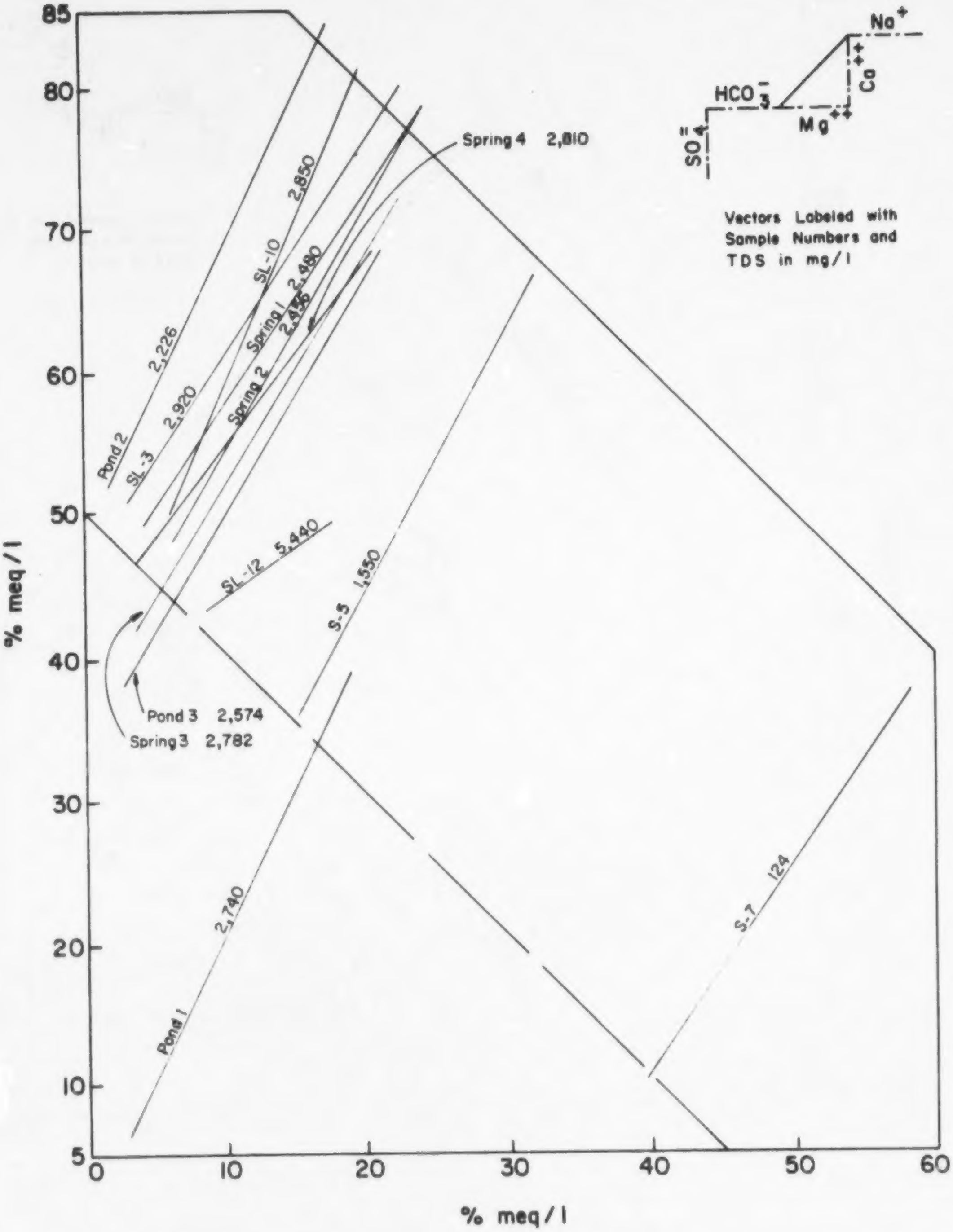


Figure 62. "Vector" diagram of water compositions. Edna Mine, Colorado.

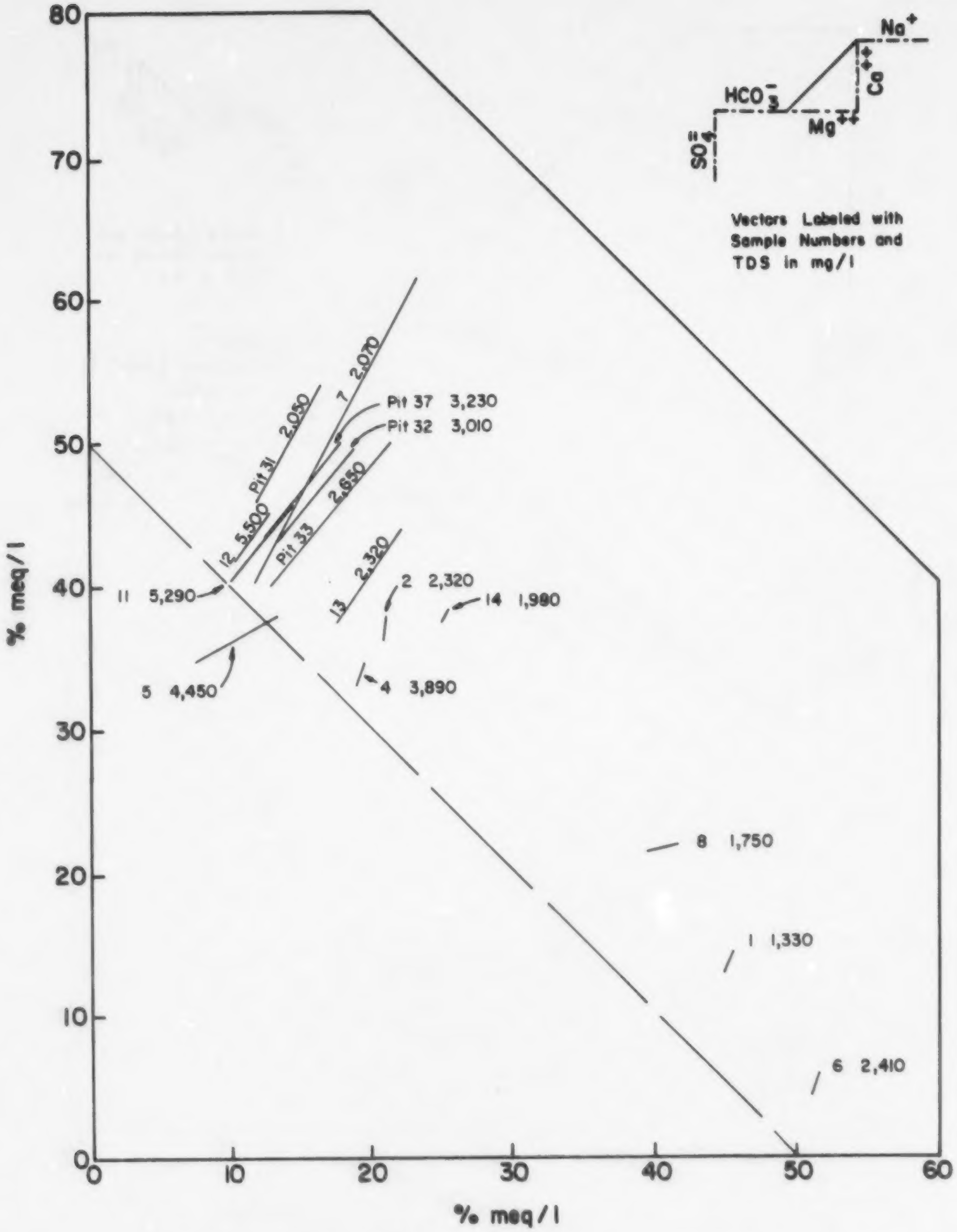


Figure 63. "Vector" diagram of water compositions. McKinley Mine, New Mexico

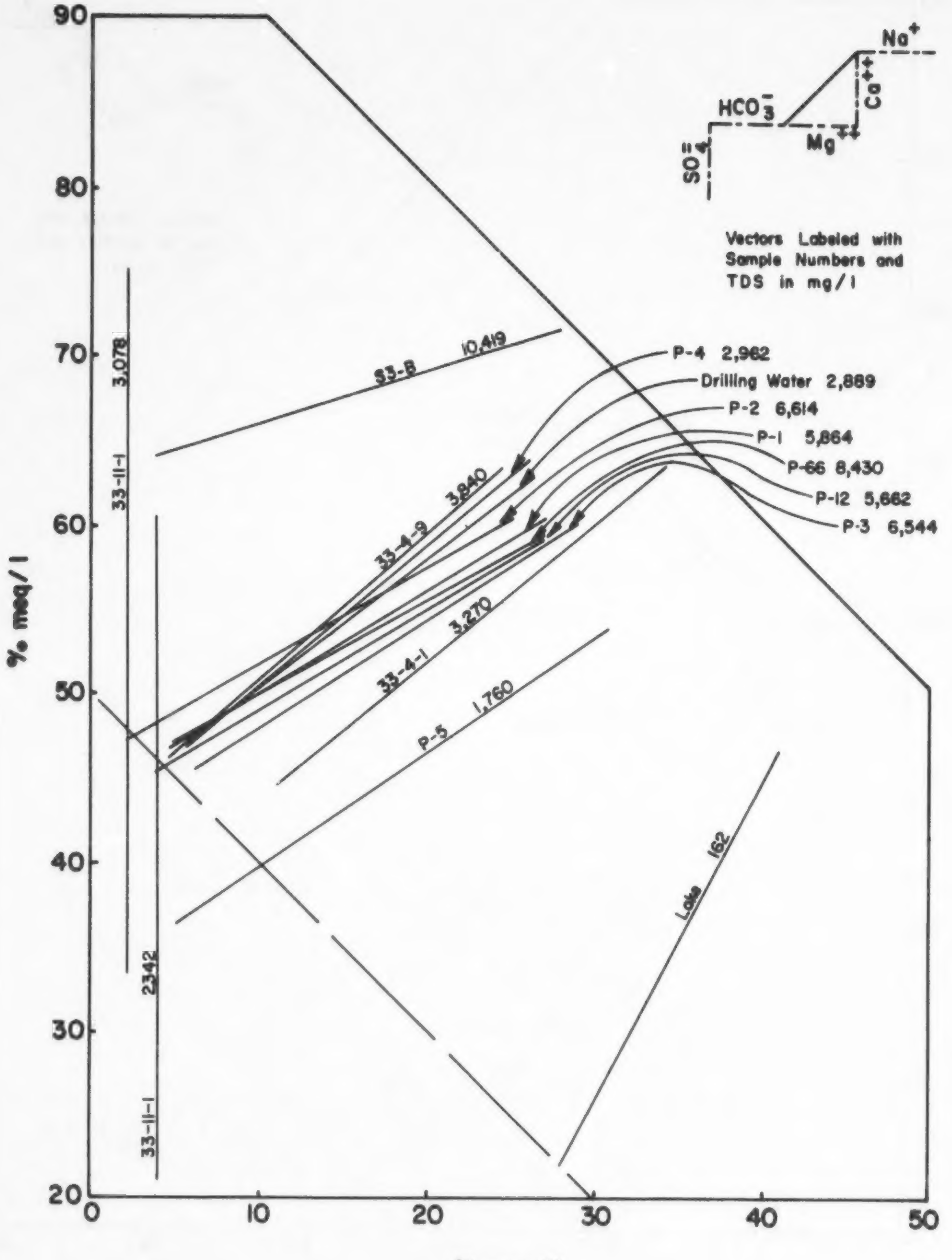


Figure 64. "Vector" diagram of water compositions. Medicine Bow Mine, Wyoming.

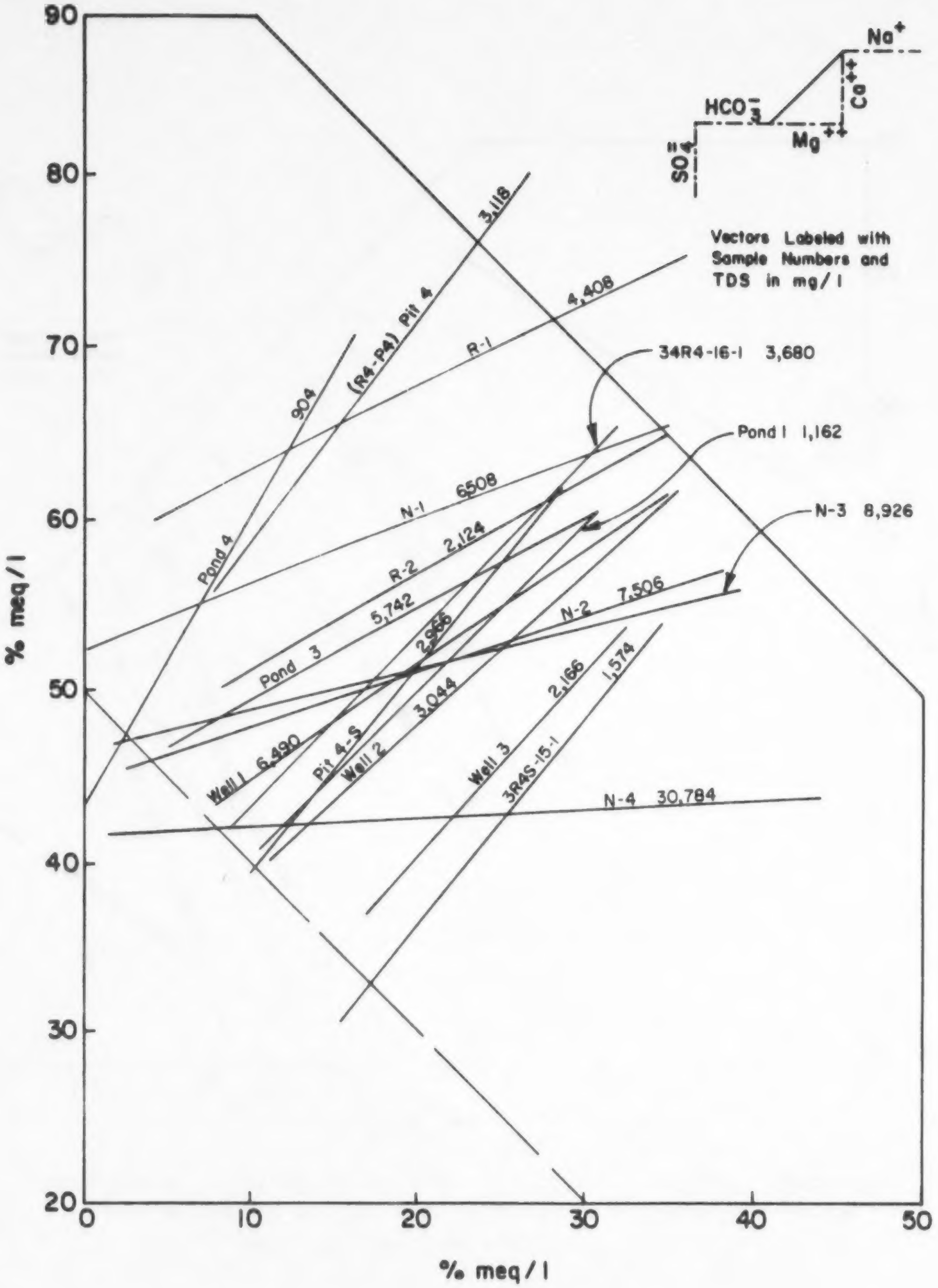


Figure 65. "Vector" diagram of water compositions. Rosebud Mine, Wyoming.

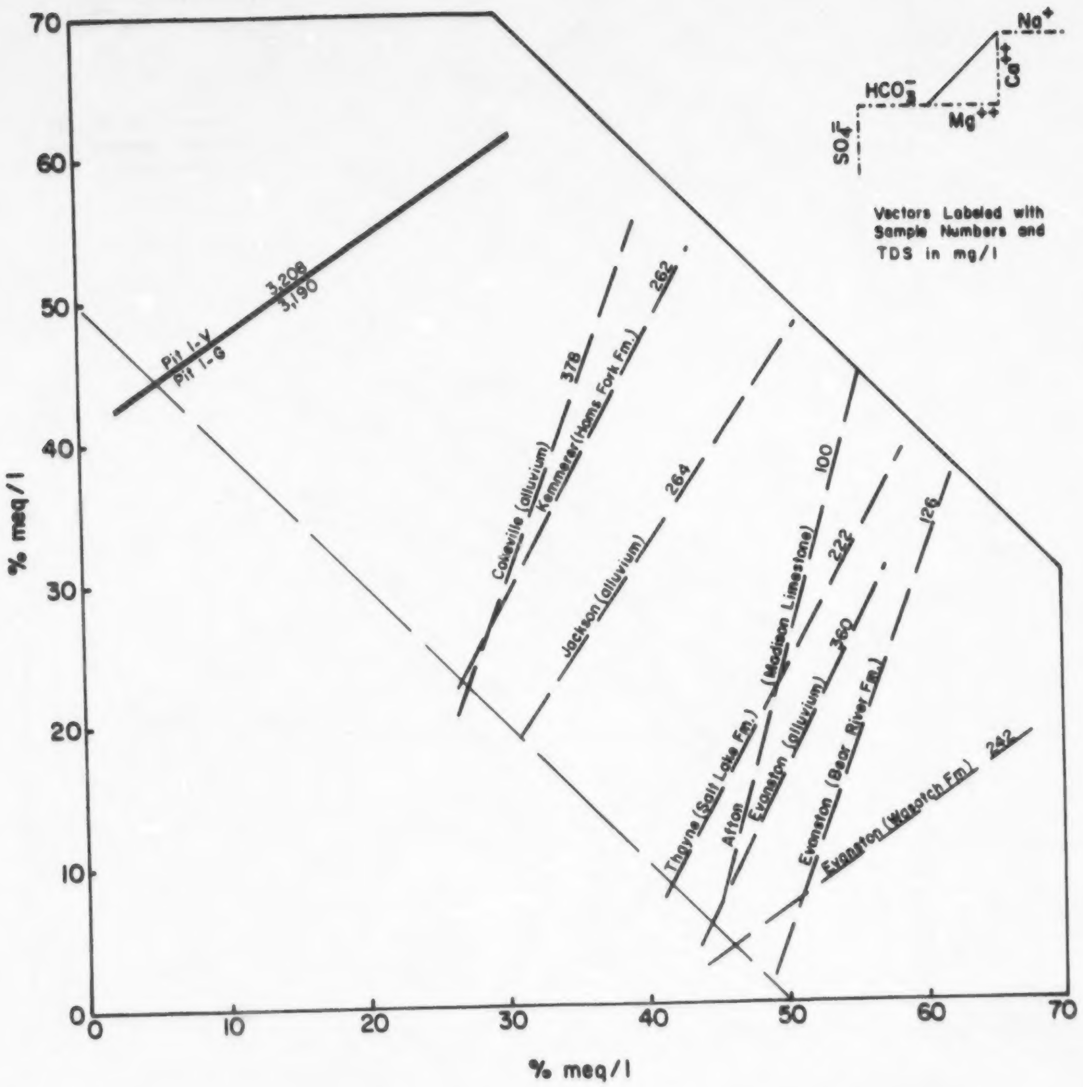


Figure 66. "Vector" diagram of water compositions. Kemmerer Mine, Wyoming. (Dashed lines from Lines and Glass (15). These analyses appear in Appendix Table C-12.)

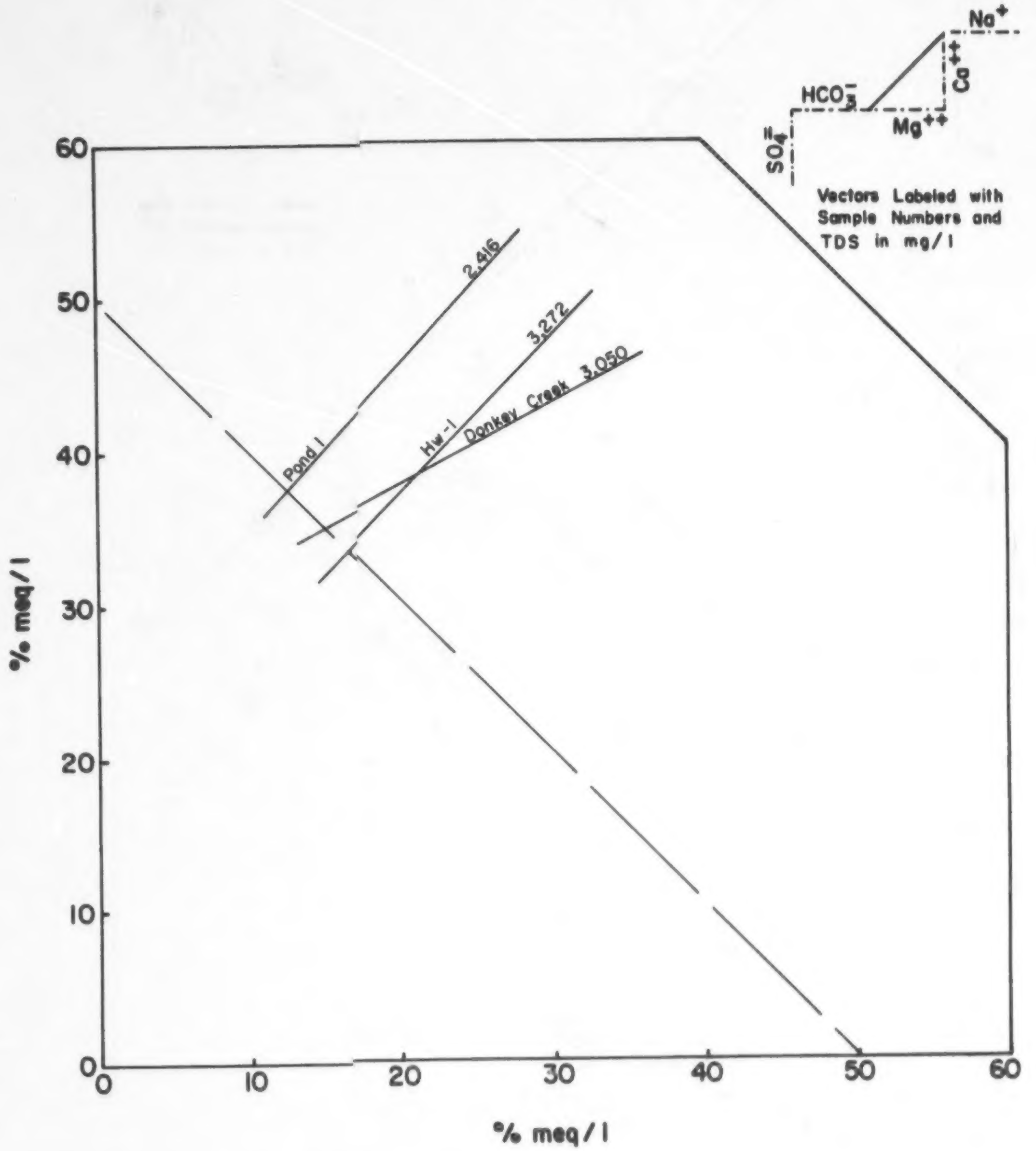


Figure 67. "Vector" diagram of water compositions. Wyodak Mine, Wyoming.

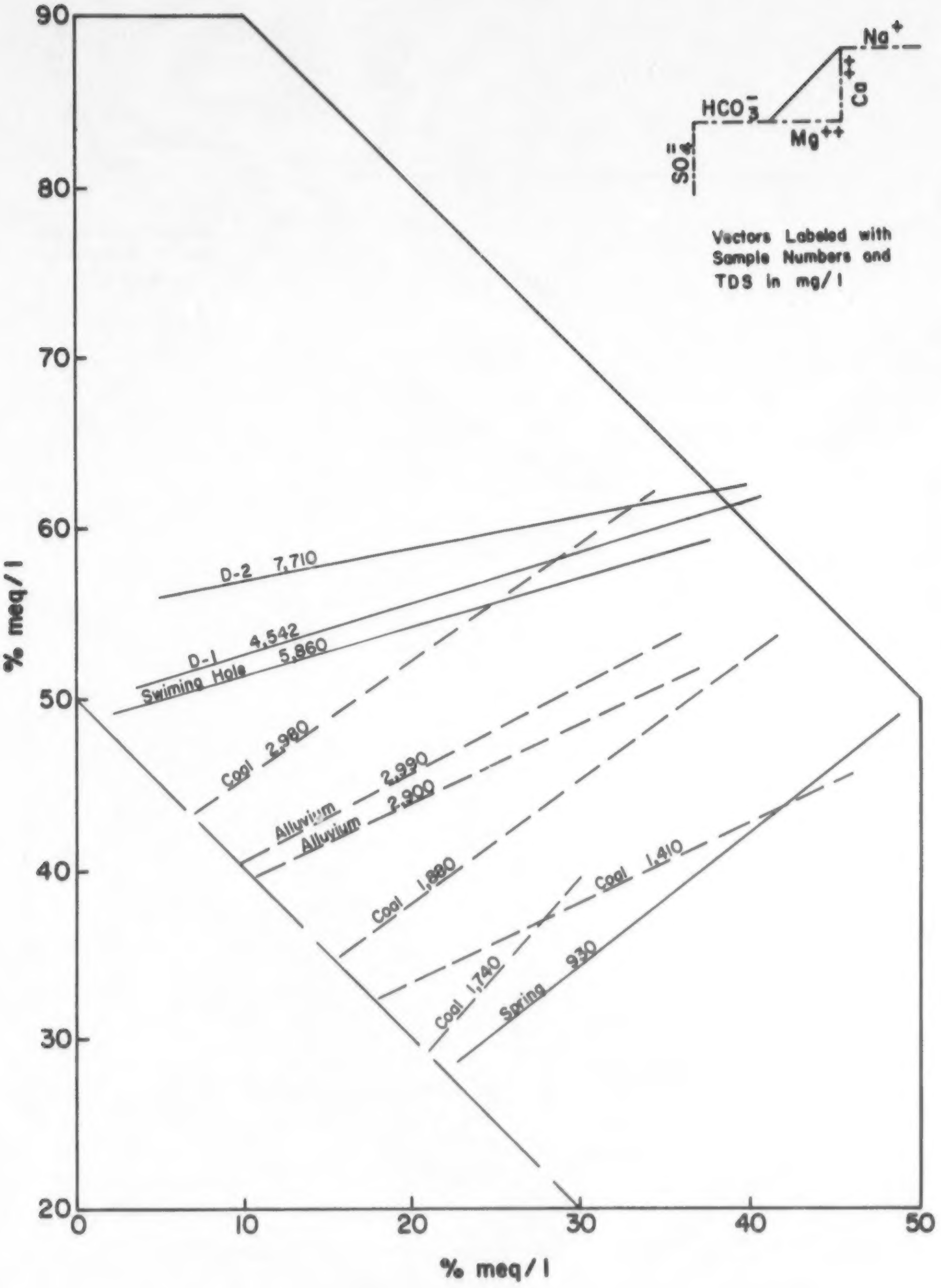


Figure 68. "Vector" diagram of water compositions. Colstrip Mine, Montana. (Data for dashed lines from Van Voast and Hedges) (35).

a. Surface waters at or downstream of a mine area.

b. Shallow alluvial aquifers below a mine.

c. Ground waters derived from shales and coals.

d. All lysimeter samples.

e. Ground waters emerging as springs from spoil piles.

These high-TDS waters were of the calcium-magnesium-sulfate type.

3. Mine areas having a confined aquifer hydrologic system show distinct groups of water chemistries.

4. Mine areas having an unconfined aquifer (water table) system do not show distinct water populations. All waters are of the calcium-magnesium-sulfate type.

Factor Analysis

Factor analysis of water data was conducted only on the Energy Fuels and Edna Mine samples. The input for this data analysis included 29 variables comprising chemistry, temperature, pH, and sample-collection time in days from an arbitrary origin. Twenty-eight samples from both mines were selected. Six significant factors were obtained:

Factor 1

TDS conductivity, Σanions, Σcations, Σions, SO_4, Ca, Sr, Mg, K, days

Factor 2

Alkalinity, HCO_3, $CO_3 + HCO_3$, CO_2, Na, (-T), (-Ca)

Factor 3

Fe, Mn, CO_2

Factor 4

pH, (-CO_2), CO_3, Si

Factor 5

O_2, (-organic C), days

Factor 6

T°, F, Ti

Factor 1 represents spoil-contact water to surface water. The inclusion of strontium in the factor indicates that the water was influenced by the dissolution of dolomite.

Factor 2 represents the deep, Type 1 waters.

Factor 3 corresponds to siderite dissolution.

Factor 4 relates the increasing solubility of silica with increasing pH.

Factor 5 relates the inverse relationship between organic carbon and dissolved oxygen.

Factor 6 relates titanium, fluoride, and temperature, but the significance of the correlation is not apparent.

Geochemical Calculations

Geochemical calculations were made for all mines investigated. The results of equilibrium water calculations are listed in Appendix Tables D-1 through D-65. Information items listed as "Input Species" were the ion concentrations (in ppm) used for each calculation. The conclusions which can be drawn from these calculations support previous observations and conclusions as to the solubilities of various minerals and potential sources for dominant ions in the waters.

The following observations can be made based on these calculations.

- In general, the concentrations of various soluble sulfate compounds such as gypsum and starkeyite were generally highest in the shallower waters, indicating that evaporation is playing an important role in controlling the ionic strength of solution. This fact is further supported by the observation that waters at or near the surface (ponds, springs issuing from spoils, and lysimeters) have the highest ionic strengths.

- The ionic strengths of lysimeter samples from the spoils, and waters emerging from the bottom of the spoils were invariably higher than overburden ground waters and were even higher than surface waters which reside atop the spoils. (See Methodology - Lysimeter Samples.)

- Calcite, dolomite, and gypsum were almost always at or near equilibrium in these waters; therefore, all will act as sources for calcium, magnesium, and bicarbonate. Calcite and gypsum will act as sinks for calcium, magnesium, and bicarbonate in the water.

- Amorphous ferric hydroxide will precipitate readily from waters containing even extremely low concentrations of iron, thus removing iron from solution.

- Waters were oversaturated with several iron and manganese species which did not appear in the rocks with which they were in contact; e.g., hematite, manganite, and birnessite. This condition indicates that these reactions are kinetically slow and that other kinetically more favorable metastable reactions are occurring, e.g., the precipitation of ferric hydroxide.

- The solubilities of sodium-bicarbonate species and calcium or magnesium-sulfate species are so high that these five ions generally constitute over 98% of the ions and ion complexes in solution.

- Aluminum in solution equilibrates rapidly by forming clays or gibbsite [$Al(OH)_3 \cdot nH_2O$].

Several conclusions can be drawn from these observations:

- Evidence indicates that waters occurring in association with the spoils are more mineralized than surface or ground waters existing outside the influence of the spoils.

- Spoil-associated waters add magnesium, calcium, and sulfate to the alluvial ground waters down-gradient of a mine.

- The controlling factor of ground-water composition is the composition of the strata through which waters flow. High sulfate waters produced in the spoil pile remain in the spoil, emerge as springs, or become mixed with the shallow ground water. Examination of drilling logs and water chemistry suggests isolation of waters by shale and clay beds in the overburden.

- Grouping of the waters according to formation source and ion chemistry yields:

Source	Dominant Ions
Sandstone	Na^+, Ca^{++}, HCO_3^-
Alluvium (above mine)	Na^+, Ca^{++}, HCO_3^-
Shale	Na^+, Ca^{++}, $SO_4^=$, HCO_3^-
Spoil (lysimeter samples)	Ca^{++}, $SO_4^=$
Surface Water Within the Mine Area	Mg^{++}, Ca^{++}, $SO_4^=$
Surface Water Outside of the Mine Area	Na, Ca^{++}, HCO_3^-

SUMMARY OF IMPORTANT CHEMICAL REACTIONS

Two different types of interactions must be considered. First, and by far the more important, are those reactions occurring in the presence of water, carbon dioxide, and free oxygen; i. e., those involving reducing waters high in organic matter. Certain reactions are not affected by the presence or absence of oxygen. These reactions are discussed below and are shown diagramatically in Figures 69 and 70.

1. Reactions independent of the presence or absence of oxygen.

   - The presence of gypsum (or anhydrite). This results in a calcium sulfate water, often with the formation of secondary gypsum deposits. The solution and reprecipitation of these minerals are generally cyclic.

   - Magnesium-sulfate-hydrate species are almost certainly secondary in origin, even when they occur in the undisturbed overburden. They are extremely soluble in water, dissolve readily, and crystallize out on evaporation of the water. The whole process is repeated numerous times when they occur in spoil piles.

   - Clay minerals under alkaline and slightly acid pH conditions will tend to remove many of the heavy metal trace elements from the water. In addition, some clays--particularly the montmorillonite group--will adsorb calcium and magnesium from the water and

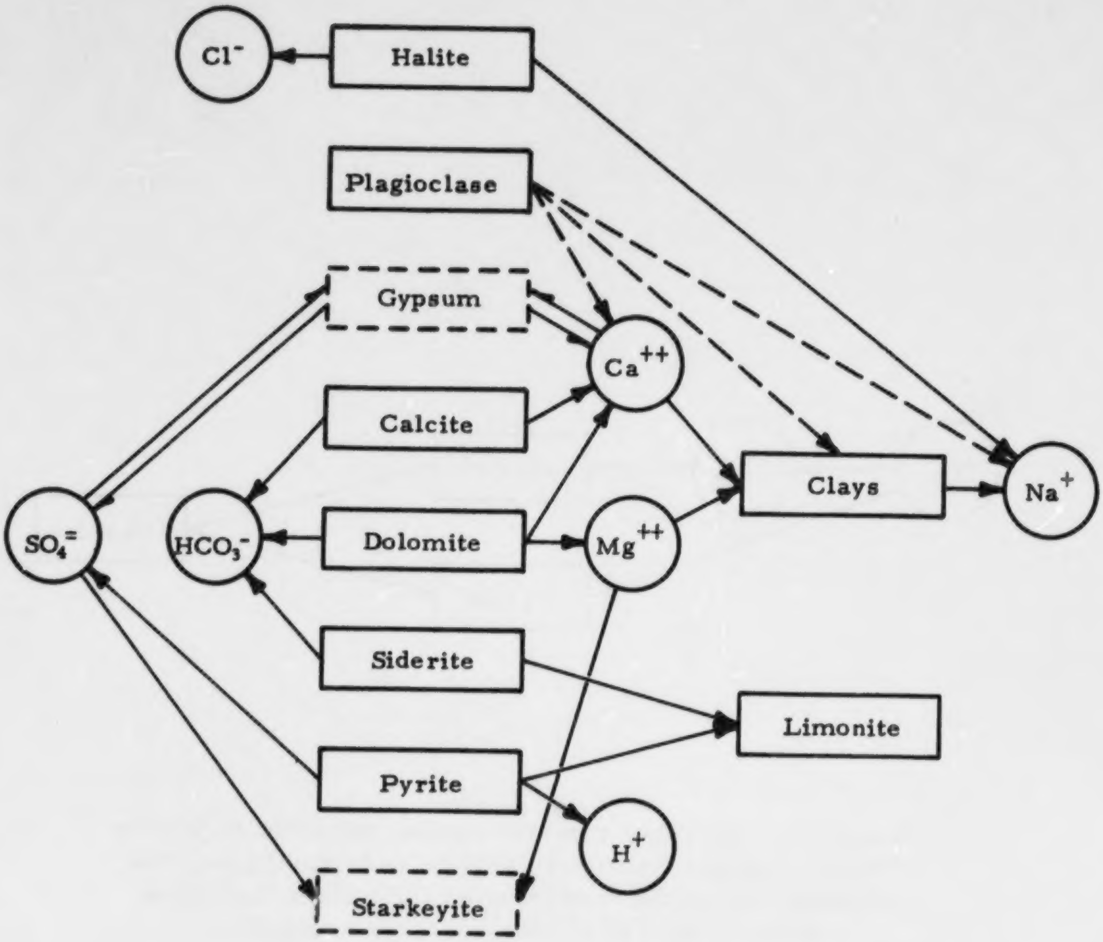

Cl⁻
Halite
Plagioclase
Gypsum
Ca⁺⁺
Calcite
Clays
Na⁺
SO₄⁼
HCO₃⁻
Dolomite
Mg⁺⁺
Siderite
Limonite
Pyrite
H⁺
Starkeyite

Figure 69. Aerobic reaction cycle: weathering of minerals in the presence of H_2O, CO_2, and O_2.

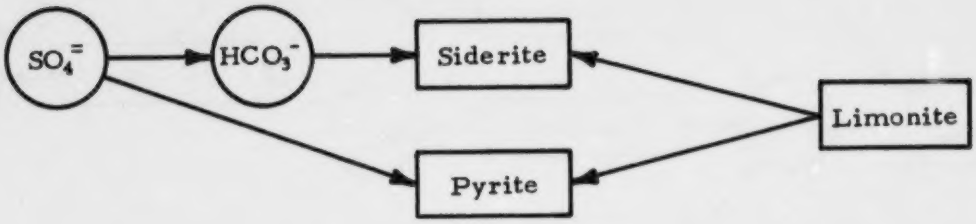

$SO_4^=$
HCO_3^-
Siderite
Pyrite
Limonite

Figure 70. Anerobic reaction cycle: anerobic reactions influenced predominantly by sulfate reduction; i. e., the oxidation of organic matter using the oxygen tied up in sulfate. Microbial catalysis is a necessity.

liberate sodium.

2. Reactions dependent on the presence of free oxygen (Figure 69).

   - Pyrite will decompose with the liberation of sulfuric acid and the precipitation of insoluble yellowish-brown ferric hydroxide, which is initially colloidal, but gradually changes to limonite and hematite. The presence of carbonates will neutralize some or all of the sulfuric acid produced.

   - Calcite will give rise to calcium sulfate waters generally with the precipitation of gypsum.

   - Dissolution of dolomite will produce calcium-magnesium-sulfate waters generally accomplished by the precipitation of gypsum and a gradual enrichment in magnesium sulfates. If the amount of pyrite exceeds that of the carbonates, acid mine drainage is a potential problem. This reaction is generally accomplished by the leaching of heavy metals from other sulfides and from clay minerals.

3. Reactions dependent on the absence of free oxygen (Figure 70).

   - The predominant reaction under the conditions of abundant organic material and no free oxygen is that of sulfate reduction, where sulfate is reduced to sulfide with the accompanying oxidation of organic carbon to bicarbonate. The generation of sulfide usually results in the formation of pyrite if any iron either in solution or as limonite is present.

Under certain pH conditions, some of the iron present may be transformed to siderite. The actual formation of either pyrite or siderite depends on a variety of factors that are not readily predictable.

Effects of Climate

In semi-arid to arid climate typical of all the sites studied, water will infiltrate into spoil piles, dissolve material, and in general return to the surface by capillary action. This process leads to the accumulation of soluble or partially soluble salts at the surface. The next influx of water redissolves these salts, and the process is repeated with a gradual increase in the quantity of these salts accumulating. A major influx of water will, however, flush many of these salts out of the spoils, probably into the highwall pits, from which they may enter the ground or surface water systems.

SECTION 9

PRESENTATION OF THE PREDICTIVE METHOD

This section describes the procedure to be followed by a mine operator in applying the predictive method developed in this study. The methodology applies only to potential coal strip-mine sites in the Western United States.

The operator may implement the predictive method by following the steps shown in the flow chart (see Figure 71). The first parameter to be characterized at the mine site is geology, followed sequentially by hydrogeology, climate, water chemistry, and mineralogy. The significance of each of these parameters is discussed below.

GEOLOGY AND HYDROGEOLOGY

The primary objective of the geological studies is to determine the structural complexity of the area to be mined. A structurally complex area will contain more than one hydrogeologic system, and each system must be evaluated separately when following the predictive method flow chart. Possible problems associated with structurally complex areas include:

- Ambiguous ground-water flow directions.
- Mixed ground-water sources.
- Greater potential for interaction of surface waters and ground waters.

For each hydrogeologic system, it is necessary to define the positions and types of aquifers present in terms of placement relative to the coal to be mined (see Figure 59). Several aquifer systems may exist at any one site, and individual aquifers may be confined or unconfined within geological strata. Where coal is below or within a confined aquifer, aquifer water will enter the mine but spoil water, if present, will not enter the aquifer unless it has access to the recharge area for that aquifer.

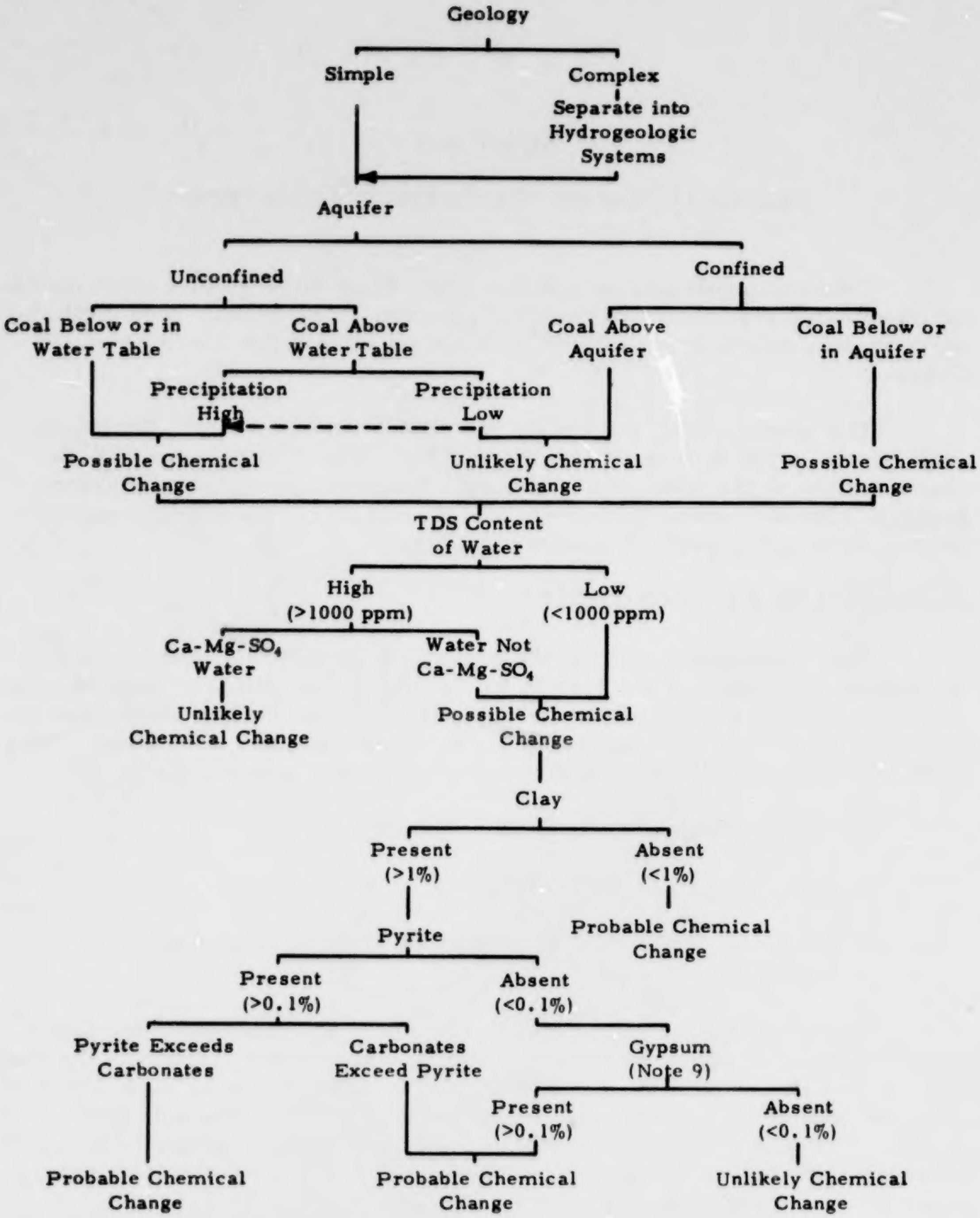

Geology
Simple
Complex
Separate into Hydrogeologic Systems
Aquifer
Unconfined
Confined
Coal Below or in Water Table
Coal Above Water Table
Coal Above Aquifer
Coal Below or in Aquifer
Precipitation High
Precipitation Low
Possible Chemical Change
Unlikely Chemical Change
Possible Chemical Change
TDS Content of Water
High (>1000 ppm)
Low (<1000 ppm)
Ca-Mg-SO4 Water
Water Not Ca-Mg-SO4
Unlikely Chemical Change
Possible Chemical Change
Clay
Present (>1%)
Absent (<1%)
Probable Chemical Change
Pyrite
Present (>0.1%)
Absent (<0.1%)
Pyrite Exceeds Carbonates
Carbonates Exceed Pyrite
Gypsum (Note 9)
Present (>0.1%)
Absent (<0.1%)
Probable Chemical Change
Probable Chemical Change
Unlikely Chemical Change

Figure 71. Predictive method flow chart.

CLIMATE

When the coal is above the water table, mining operations are unlikely to cause changes in ground-water chemistry unless precipitation infiltrates through the spoils and into the underlying ground water. This will result only where precipitation is high or where the distribution of precipitation is uneven. However, this condition is unlikely to occur over the semiarid West where precipitation is low and where evaportranspiration exceeds precipitation. The meteorological conditions must be determined at the site before this generality can be assumed to hold.

WATER CHEMISTRY

Water samples must be obtained from each aquifer, and samples must be analyzed according to standard procedures. Conductivity, pH, dissolved oxygen, and hydrogen sulfide should be measured in the field at the time of sample collection. Laboratory analysis of each water sample from all confined and unconfined aquifers should be made to determine the major chemical constituents: calcium, magnesium, sodium, potassium, sulfate, bicarbonate, carbonate, chloride, and the TDS content.

A "vector" diagram representing the water compositions, and the field determinations, while not directly applicable to the flow chart, will assist the operator in understanding the ground-water conditions. TDS content of the water best describes its quality for purposes of application of this method. The dividing line of 1,000 mg/l, although somewhat arbitrary, is used by the U. S. Geological Survey to distinguish between saline and nonsaline waters. The next flowsheet criteria are the calcium, magnesium, and potassium content of the waters. Ground waters low in TDS, or with a chemical composition other than calcium, magnesium, and potassium could be subjected to a drastic chemical change if mixed with spoil water because spoil waters are generally high in TDS with a calcium-magnesium-potassium composition. Waters must be considered chemically indistinguishable from spoil water if two-thirds of the ions (expressed as meq/l) consist of calcium, magnesium, and sulfate, and if the TDS exceeds 1,000 mg/l.

MINERALOGY

The final parameter considered in the chart is the mineral content of the overburden determined from either cores or drill cutting samples. A lithologic column, preferably prepared from core data, is necessary to determine the number and type of rock units in the overburden. Samples of each lithologic type are to be submitted for mineralogical analysis by x-ray diffraction. A clay-size separation is also to be made on each sample and the amount and types of clay minerals determined.

The critical minerals whose presence or absence must be ascertained are: clays, carbonates, pyrite, and gypsum, and other sulfates. One method of compiling this data is to prepare a table containing the various rock units, the percent of the overburden that each rock unit represents, and the composition of the rock unit as determined by x-ray diffraction. If neither gypsum nor pyrite is detected by x-ray diffraction, but either is found in the core (either visually or by staining tests), then 1% of each is to be assumed.

If clays comprise less than 1% of the overburden, they should be considered absent for the purposes of this study. In the rare case where clay is not present, heavy-metal trace elements may be present in the water, and these elements could result in a major change in ground water chemistry.

Pyrite and gypsum are considerably more reactive than clay minerals, and the distinction between their presence or absence should be set at 0.1%. If the overall quantity of pyrite in the overburden is greater than the quantity of carbonate that could neutralize sulfuric acid formed by pyrite decomposition, then acid mine drainage is a potential problem. If gypsum or other sulfate minerals are present, or if calcium-magnesium sulfate is formed by the neutralization of the sulfuric acid from pyrite, then the spoil water will contain calcium-magnesium sulfates.

It must be emphasized that throughout this study, value judgments pertaining to the possible effects of ground-water chemical changes observed and predicted were not made, nor intended. Such judgments were considered to be beyond the scope of the project.

REFERENCES

1. Gleason, V., and Russell, Henry H., 1976. Coal and the Environment Abstract Series: Mine Drainage Bibliography, 1910-1976. Bituminous Coal Research, Inc.

2. Caruccio, F. T., 1973. Characterization of Strip Mine Drainage by Pyrite Grain Size and Chemical Quality of Ground Water, In: Ecology and Reclamation of Devastated Land. Ed. Russell Hutnik and Grant Davis, p. 193-226.

3. McWhorter, D. B., and Rome, J. W., 1976. Inorganic Water Quality in a Surface Mined Watershed. Paper presented at: American Geophysical Union Symposium on Methodologies for Environmental Assessments in Energy Development Regions. Dec. 8, 1976, San Francisco, California.

4. Averitt, Paul, 1972. Geologic Atlas of the Rocky Mountain Region. Rocky Mountain Association of Geologists, Denver, Colorado.

5. Weimer, R. J., 1977. Stratigraphy and Tectonics of Western Coals. In: Geology of Rocky Mountain Coal. A symposium, Keith Murray, ed. Colorado Geological Survey, Denver, Colorado.

6. Wyoming State Engineers Office, 1970. Water and Related Land Resources of the Green River, Wyoming. Wyoming Water Planning Program Report No. 3.

7. Wyoming State Engineers Office, 1972. Water and Related Land Resources of Northeastern Wyoming. Wyoming Water Planning Program Report No. 10.

8. Lowry, M. E., et al, 1973. Water Resources of the Laramie, Shirley, Hanna Basins, and Adjacent Areas, Southwestern Wyoming. U. S. Geol. Survey Hydrologic Investigations Atlas HA-471.

9. Glass, G. B., 1976. Review of Wyoming Coal Fields, 1976. Geological Survey of Wyoming Public Information Circular No. 4.

10. Van der Leeden, F., Cerrillo, L. A., and Miller, D. W., 1975. Ground-Water Pollution Problems in the Northwestern United States. EPA-660/3-75--18, U.S. Environmental Protection Agency, Ada, Oklahoma.

11. Shomaker, J. W., Beaumont, E. C., and Kottlowski, F. E., 1971. Strippable Low-sulfur Coal Resources of the San Juan Basin in New Mexico and Colorado. New Mexico Bureau of Mines and Min. Resources Memoir 25.

12. Fassett, J. E., 1976. Stratigraphy of Coals of the San Juan Basin. In: Geology of Rocky Mountain Coal. A Symposium, Keith Murray ed. Colo. Geol. Survey, Denver, Colorado.

13. Scalf, M. R., Keeley, J. W. and daFenes, C. J., 1973. Groundwater Pollution in the South Central States: EPA-R2-73-268. Environmental Protection Agency, Ada, Oklahoma.

14. Shomaker, J. W., and Stone, W. J., 1976. Availability of Groundwater for Coal Development in the San Juan Basin, New Mexico. In: Guidebook to Coal and Geology of Northwest New Mexico. New Mexico Bureau of Mines and Mineral Resources Circular 154.

15. Lines, G. C., and Glass, W. R., 1975. Water Resources of the Thrust Belt of Western Wyoming. U.S. Geol. Survey Hydrologic Investigations Atlas HA-539.

16. Glass, G. B., 1977. Wyoming Coal Deposits. In: Geology of Rocky Mountain Coal. A Symposium, Keith Murray, ed. Colo. Geol. Survey, Denver, Colorado.

17. Wyoming State Engineer's Office, 1972. Water and Related Land Resources of Northwestern Wyoming. Wyoming Water Planning Program Report No. 10.

18. Hodson, W. G., Pearl, R. H., and Druse, S. A., 1973. Water Resources in the Powder River Basin and Adjacent Areas, Northeastern Wyoming. U.S. Geol. Survey Hydrologic Investigations Atlas HA-465.

19. Denson, N. M., and Keefer, W. R., 1974. Map of the Wyodak-Anderson Coal Bed in the Gillette Area, Campbell County, Wyoming. U.S. Geol. Survey Misc. Inv. Series Map I-848-D.

20. King, N. J., 1974, Maps Showing Occurrence of Ground Water in the Gillette Area, Campbell County, Wyoming. U.S. Geol. Survey Misc. Inv. Series Map I-848-E.

21. Hansen, E. A., and Harris, A. R., 1975. Validity of Soil-Water Samples Collected with Porous Ceramic Cups. Soil Sci. of Am. Proc., V. 39, No. 3.

22. Bass, N. W., Eby, J. B., and Campbell, M. R., 1955. Geology and Mineral Fuels of Parts of Routt and Moffat Counties, Colorado. U. S. Geol. Survey Bull. 1027-D, pp. 143-177.

23. Fenneman, W. M., and Gale, H. S., 1906. The Yampa Coal Field, Routt County, Colorado. U. S. Geol Survey Bull. 297.

24. Boettcher, A. J., 1972. Ground-Water Occurrence in Northern and Central Parts of Western Colorado. Colorado Water Resources Circular 15.

25. Cooley, M. E., Harshbarger, J. W., Abers, J. P., and Hardt, W. F., 1969. Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah. U. S. Geol. Survey Prof. Paper 521-A.

26. EMRIA, 1975. Energy Mineral Rehabilitation Inventory and Analysis - Hanna Coal Field, Carbon County, Wyoming. EMRIA Report No. 2. Bureau of Land Management, Bureau of Reclamation, U. S. Geological Survey, and U. S. Department of the Interior.

27. Davis, R. W., 1977. A Report on the Ground-Water Hydrology of the Medicine Bow Mine, Carbon County, Wyoming. Westinghouse Electric Corporation, Environmental Systems Department, Pittsburgh, Pennsylvania.

28. U. S. Geological Survey Water Resources Data for Wyoming, 1975. Platte River Basin and Hanna Draw.

29. Glass, G. B., 1972. Mining in the Hanna Coal Field. Geological Survey of Wyoming.

30. Rubey, W. W., Oriel, S. S., and Tracey, J. I., Jr., 1975. Geology of the Sage and Kemmerer 15 Minute Quadrangles, Lincoln County, Wyoming. U. S. Geol. Survey Prof. Paper 855.

31. Denson, N. M., Keefer, W. R., and Horn, G. H., 1974. Coal Resources in the Gillette Area, Wyoming. U. S. Geol. Survey Misc. Inv. Series Map I-848-C.

32. Hadley, R. F., and Keefer, W. R., 1975. Map Showing Some Potential Effects of Surface Mining of the Wyodak-Anderson Coal, Gillette Area, Campbell County, Wyoming. U. S. Geol. Survey Misc. Inv. Series Map I-848-F.

33. Matson, R. E., and Blumer, J. W., 1973. Quality and Reserves of Strippable Coal, Selected Deposits, Southeastern Montana, Mont. Bureau of Mines and Geol. Bull. 91.

34. Van Voast, W., and Hedges, R. B., 1976. Hydrogeologic Conditions and Projections Related to Mining Near Colstrip Mine, Montana. Mont. Bureau of Mines and Geol. Open File Report, June, 1976.

35. Plummer, N., Jones, B. F., and Truesdell, A. H., 1976. WATEQF: A Fortran IV Version of WATEQ, A Computer Program of Calculating Chemical Equilibrium of Natural Waters. NTIS PB-261 027, Reston, Virginia.

36. Garrels, R. M., and Thompson, M. E., 1962. A Chemical Model for Sea Water at 250°C and One Atmosphere Total Pressure. Am. Jour. Sci., V. 260, p. 57-66.

37. Hem, J. D., 1970. Study and Interpretations of the Chemical Characteristics of Natural Water. U. S. Geol. Survey Water-Supply Paper 1473.

38. Stiff, H. A., 1951. The Interpretation of Chemical Water Analyses by Means of Patterns. Jour. Petroleum Technology, V. 3, No. 10, pp. 15-17.

39. Korzhinskii, D. S., 1959. Physiochemical Basis of the Analysis of the Paragenesis of Minerals. Consultants Bureau, Inc., New York.

40. Hounslow, A. W., 1965. Chemical Petrology of Some Greenville Schists Near Fernleigh, Ontario. M.Sc. Thesis, Carleton University, Ottowa, Ontario.

41. Geraghty, J. J., Miller, D. W., Van der Leeden, F., and Troise, F. L., 1973. Water Atlas of the United States. Water Information Center, Port Washington, New York.

GLOSSARY OF MINERAL SPECIES

Anhydrite	$CaSO_4$
Arcanite	K_2SO_4
Birnessite	$(Na,Ca)Mn_7O_{14} \cdot 3H_2O$
Calcite	$CaCO_3$
Chalcedony	microcrystalline SiO_2
Dolomite	$CaMg(CO_3)_2$
Feldspar	$NaAlSi_3O_8$ - $KAlSi_3O_8$ - $CaAl_2Si_2O_8$
Fluorapatite	$Ca_5(PO_4)_3F$
Gibbsite	$Al(OH)_3$
Goethite	α-$FeO(OH)$
Gypsum	$CaSO_4 \cdot 2H_2O$
Hematite	α-Fe_2O_3
Hexahydrite	$MgSO_4 \cdot 6H_2O$
Illite	$(K,H_3O)(Al,Mg,Fe)_2(Al,Si)_4O_{10}[(OH)_2 \cdot H_2O]$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Limonite	general term for any hydrous iron oxide, mostly goethite
Magnetite	Fe_2O_4
Manganite	$MnO(OH)$
Montmorillonite	$(Na,Ca)_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$
Pyrite	FeS_2
Quartz	SiO_2
Rhodocrosite	$MnCO_3$
Rozenite	$Fe^{+2}SO_4 \cdot 4H_2O$
Siderite	$FeCO_3$
Silica Gel	amorphous SiO_2
Thenardite	Na_2SO_4
Vermiculite	$(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2 \cdot 4H_2O$
Vivianite	$Fe_3^{+2}(PO_4)_2 \cdot 8H_2O$

APPENDIX A

BORE HOLE DATA AND FIELD LOGS

LEGEND

▨ Spoil or road fill (mixed SS, SHL, and coal)

▤ Shale or clay, SHL, CLY

▦ Siltstone, SLTS

▩ Sandstone, SS

■ Coal

▒ Sand and gravel, SD and GRVL

⌶ Perforated zone or open hole (see Figure 9, Text)

↓ Lysimeter, cross at bottom (see Figure 10, Text)

▽ 6946, static water level and elevation

△ Total depth of hole, TD-53'

← Water first encountered

DESCRIPTION ABBREVIATIONS

DK	DARK	F	FINE	CARBON.	CARBONACEOUS
LT	LIGHT	MED	MEDIUM	TR	TRACE
CAL	CALCAREOUS	CRSE	COARSE	ALT	ALTERNATING
HD	HARD	BLDRS	BOULDERS	MTRL	MATERIAL
GRY	GRAY	CBLES	COBBLES	SMPL	SAMPLE
BRN	BROWN	WTHRD	WEATHERED		
YLW	YELLOW	W/	WITH		
SDY	SANDY	UNCON	UNCONSOLIDATED		
SLTY	SILTY				
CLYEY	CLAYEY				

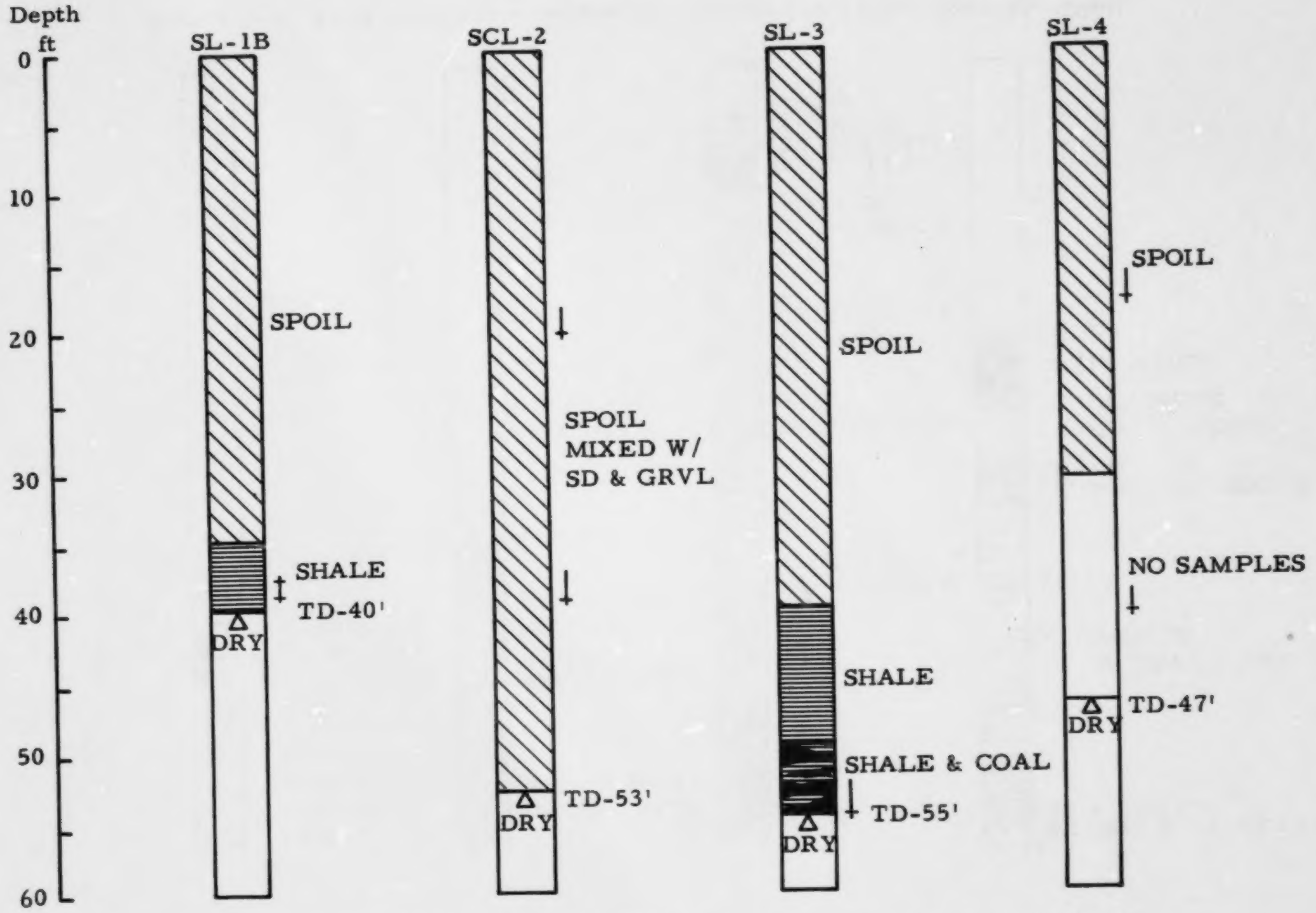

Depth
ft
0
10
20
30
40
50
60
SL-1B
SPOIL
SHALE
TD-40'
DRY
SCL-2
SPOIL
MIXED W/
SD & GRVL
TD-53'
DRY
SL-3
SPOIL
SHALE
SHALE & COAL
TD-55'
DRY
SL-4
SPOIL
NO SAMPLES
TD-47'
DRY

Figure A-1. Field log and hole completion. Energy Fuels Mine, Colorado.

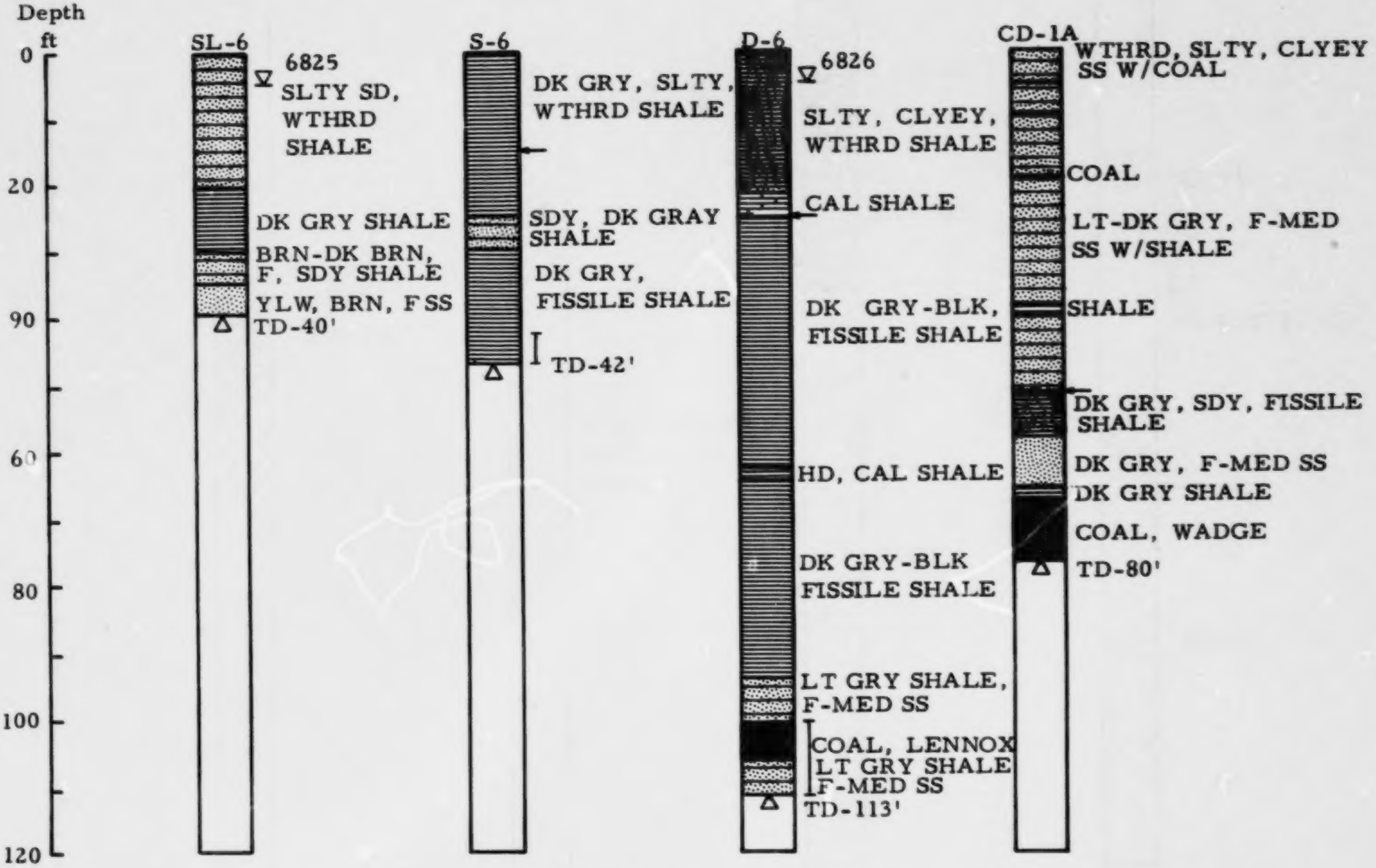

Depth
ft
0
20
90
60
80
100
120
SL-6
6825
SLTY SD, WTHRD SHALE
DK GRY SHALE
BRN-DK BRN, F, SDY SHALE
YLW, BRN, FSS
TD-40'
S-6
DK GRY, SLTY, WTHRD SHALE
SDY, DK GRAY SHALE
DK GRY, FISSILE SHALE
TD-42'
D-6
6826
SLTY, CLYEY, WTHRD SHALE
CAL SHALE
DK GRY-BLK, FISSILE SHALE
HD, CAL SHALE
DK GRY-BLK FISSILE SHALE
LT GRY SHALE, F-MED SS
COAL, LENNOX
LT GRY SHALE
F-MED SS
TD-113'
CD-1A
WTHRD, SLTY, CLYEY SS W/COAL
COAL
LT-DK GRY, F-MED SS W/SHALE
SHALE
DK GRY, SDY, FISSILE SHALE
DK GRY, F-MED SS
DK GRY SHALE
COAL, WADGE
TD-80'

Figure A-1. Field log and hole completion. Energy Fuels Mine, Colorado (Cont).

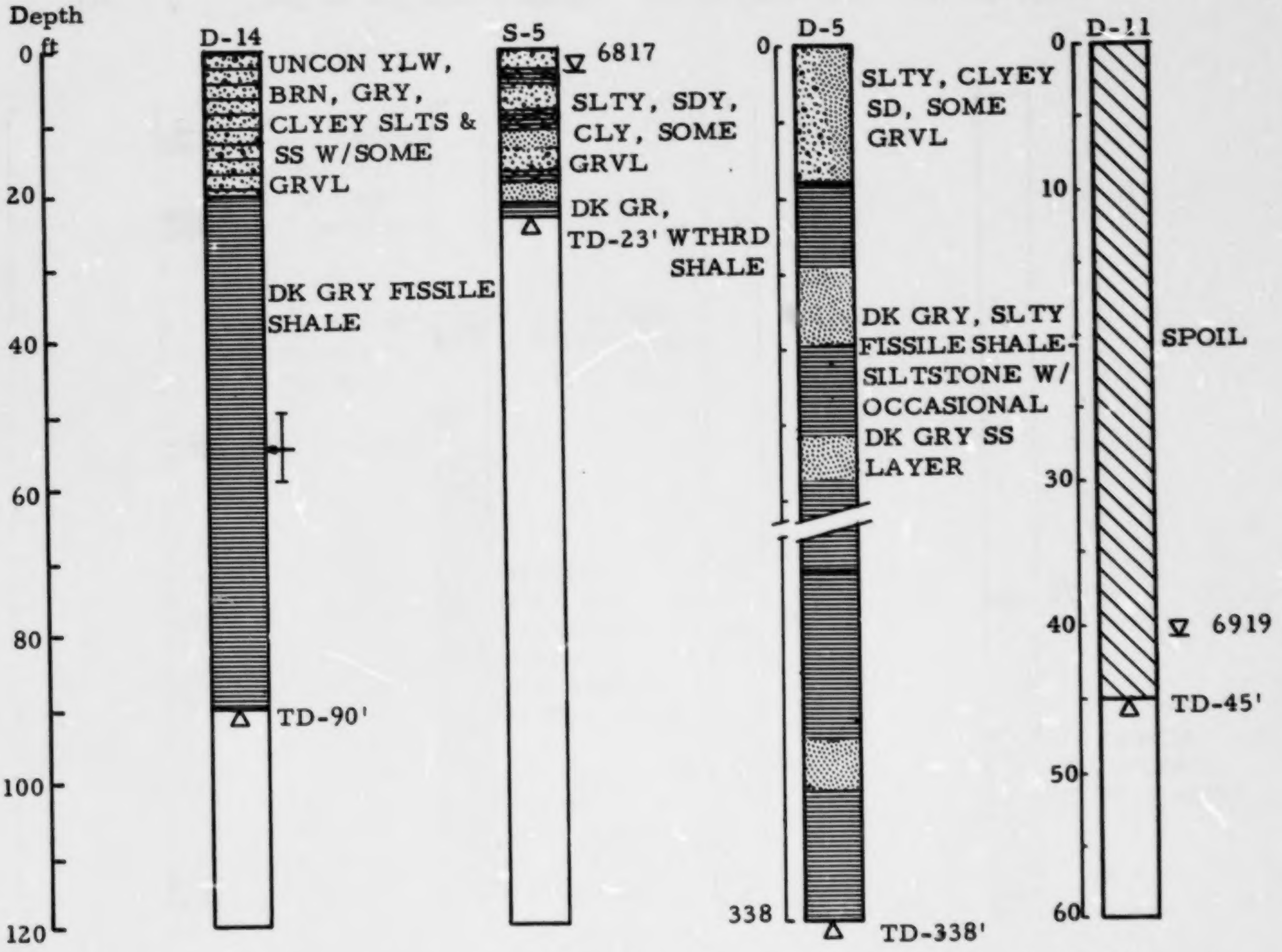

Depth
0 ft
20
40
60
80
100
120
D-14
UNCON YLW, BRN, GRY, CLYEY SLTS & SS W/SOME GRVL
DK GRY FISSILE SHALE
TD-90'
S-5
6817
SLTY, SDY, CLY, SOME GRVL
DK GR, TD-23' WTHRD SHALE
D-5
0
338
SLTY, CLYEY SD, SOME GRVL
DK GRY, SLTY FISSILE SHALE-SILTSTONE W/ OCCASIONAL DK GRY SS LAYER
TD-338'
D-11
0
10
30
40
50
60
SPOIL
6919
TD-45'

Figure A-1. Field log and hole completion. Energy Fuels Mine, Colorado (Cont).

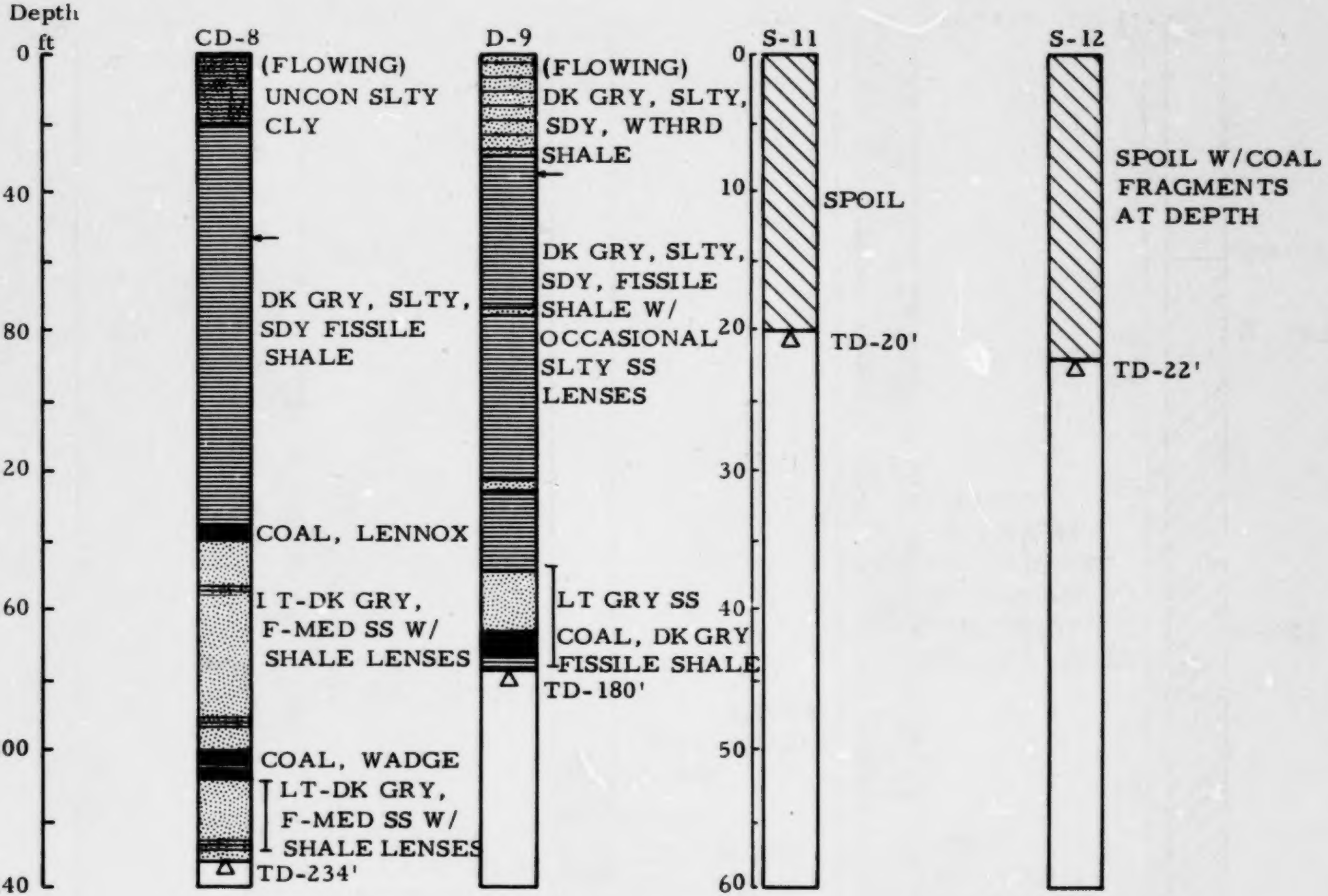

Depth ft
0
40
80
120
160
200
240
CD-8
(FLOWING)
UNCON SLTY CLY
DK GRY, SLTY, SDY FISSILE SHALE
COAL, LENNOX
LT-DK GRY, F-MED SS W/ SHALE LENSES
COAL, WADGE
LT-DK GRY, F-MED SS W/ SHALE LENSES
TD-234'
D-9
(FLOWING)
DK GRY, SLTY, SDY, WTHRD SHALE
DK GRY, SLTY, SDY, FISSILE SHALE W/ OCCASIONAL SLTY SS LENSES
LT GRY SS
COAL, DK GRY FISSILE SHALE
TD-180'
S-11
0
10
20
30
40
50
60
SPOIL
TD-20'
S-12
SPOIL W/COAL FRAGMENTS AT DEPTH
TD-22'

Figure A-1. Field log and hole completion. Energy Fuels Mine, Colorado (Cont).

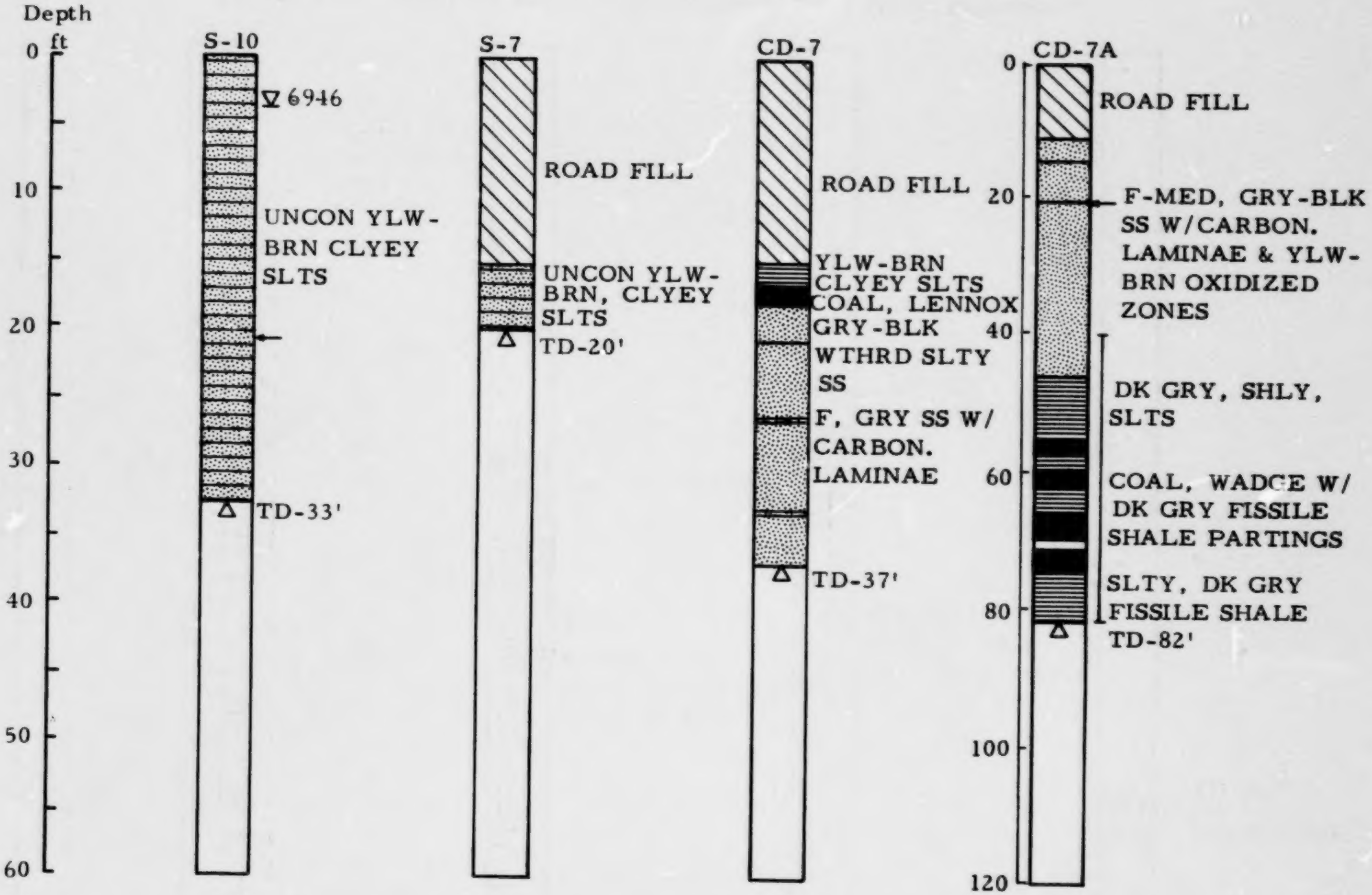

Depth
ft
0
10
20
30
40
50
60
S-10
6946
UNCON YLW-BRN CLYEY SLTS
TD-33'
S-7
ROAD FILL
UNCON YLW-BRN, CLYEY SLTS
TD-20'
CD-7
ROAD FILL
YLW-BRN CLYEY SLTS
COAL, LENNOX
GRY-BLK WTHRD SLTY SS
F, GRY SS W/ CARBON. LAMINAE
TD-37'
CD-7A
0
20
40
60
80
100
120
ROAD FILL
F-MED, GRY-BLK SS W/CARBON. LAMINAE & YLW-BRN OXIDIZED ZONES
DK GRY, SHLY, SLTS
COAL, WADGE W/ DK GRY FISSILE SHALE PARTINGS
SLTY, DK GRY FISSILE SHALE
TD-82'

Figure A-1. Field log and hole completion. Energy Fuels Mine, Colorado (Cont).

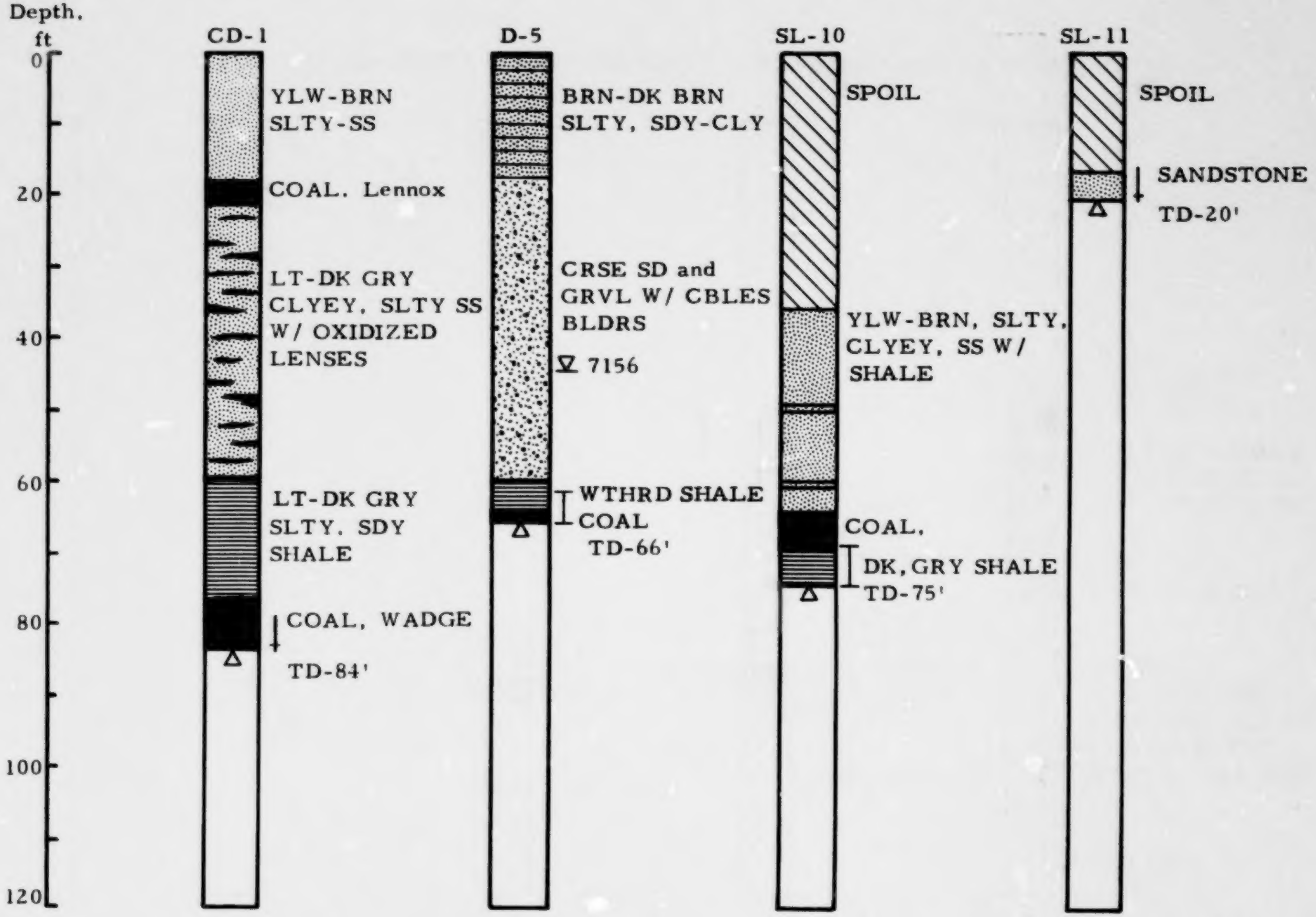

Depth, ft
0
20
40
60
80
100
120
CD-1
YLW-BRN SLTY-SS
COAL. Lennox
LT-DK GRY CLYEY, SLTY SS W/ OXIDIZED LENSES
LT-DK GRY SLTY. SDY SHALE
COAL, WADGE
TD-84'
D-5
BRN-DK BRN SLTY, SDY-CLY
CRSE SD and GRVL W/ CBLES BLDRS
7156
WTHRD SHALE
COAL
TD-66'
SL-10
SPOIL
YLW-BRN, SLTY, CLYEY, SS W/ SHALE
COAL.
DK, GRY SHALE
TD-75'
SL-11
SPOIL
SANDSTONE
TD-20'

Figure A-2. Field log and hole completion. Edna Mine, Colorado.

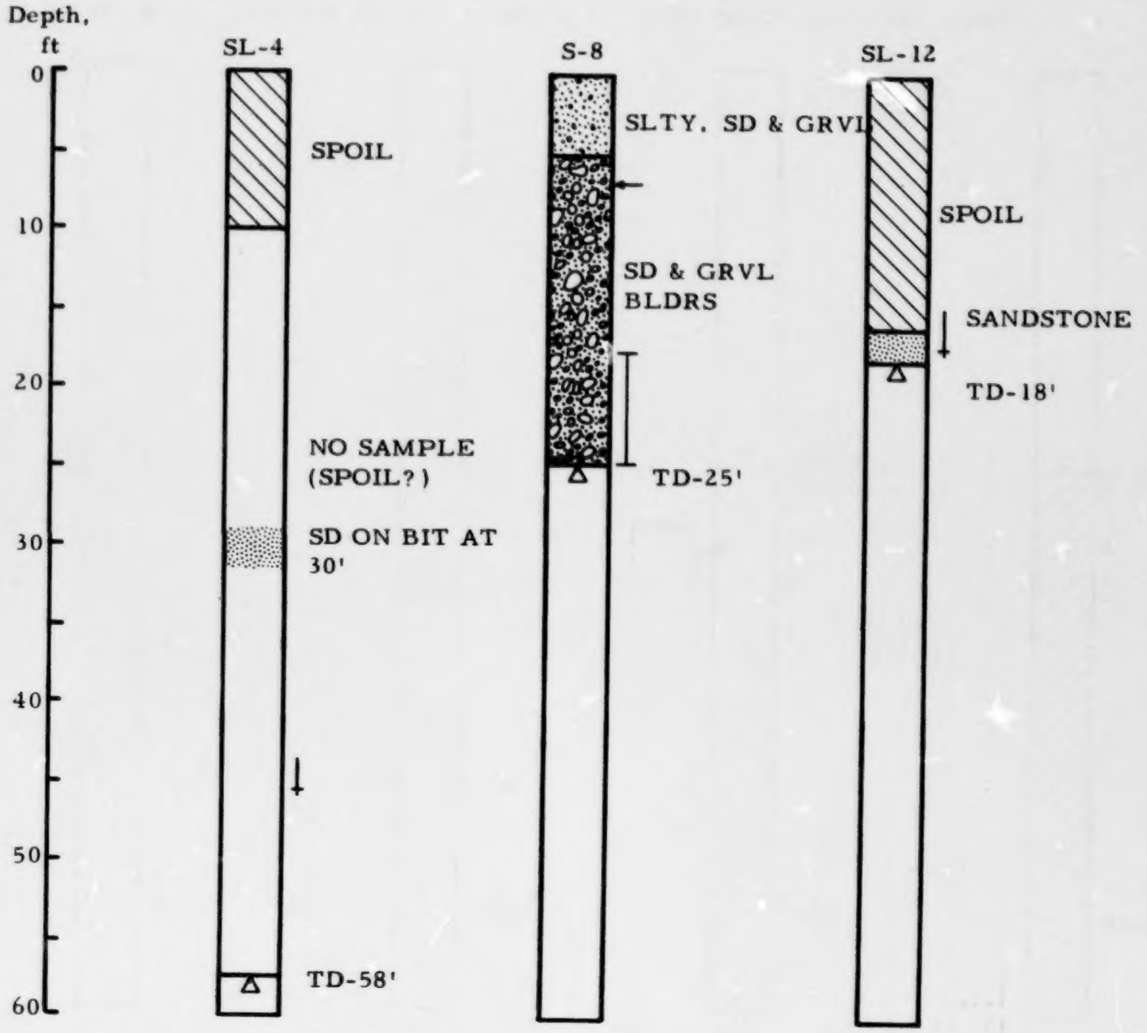

Depth, ft
0
10
20
30
40
50
60
SL-4
SPOIL
NO SAMPLE (SPOIL?)
SD ON BIT AT 30'
TD-58'
S-8
SLTY, SD & GRVL
SD & GRVL BLDRS
TD-25'
SL-12
SPOIL
SANDSTONE
TD-18'

Figure A-2. Field log and hole completion. Edna Mine, Colorado (Cont.).

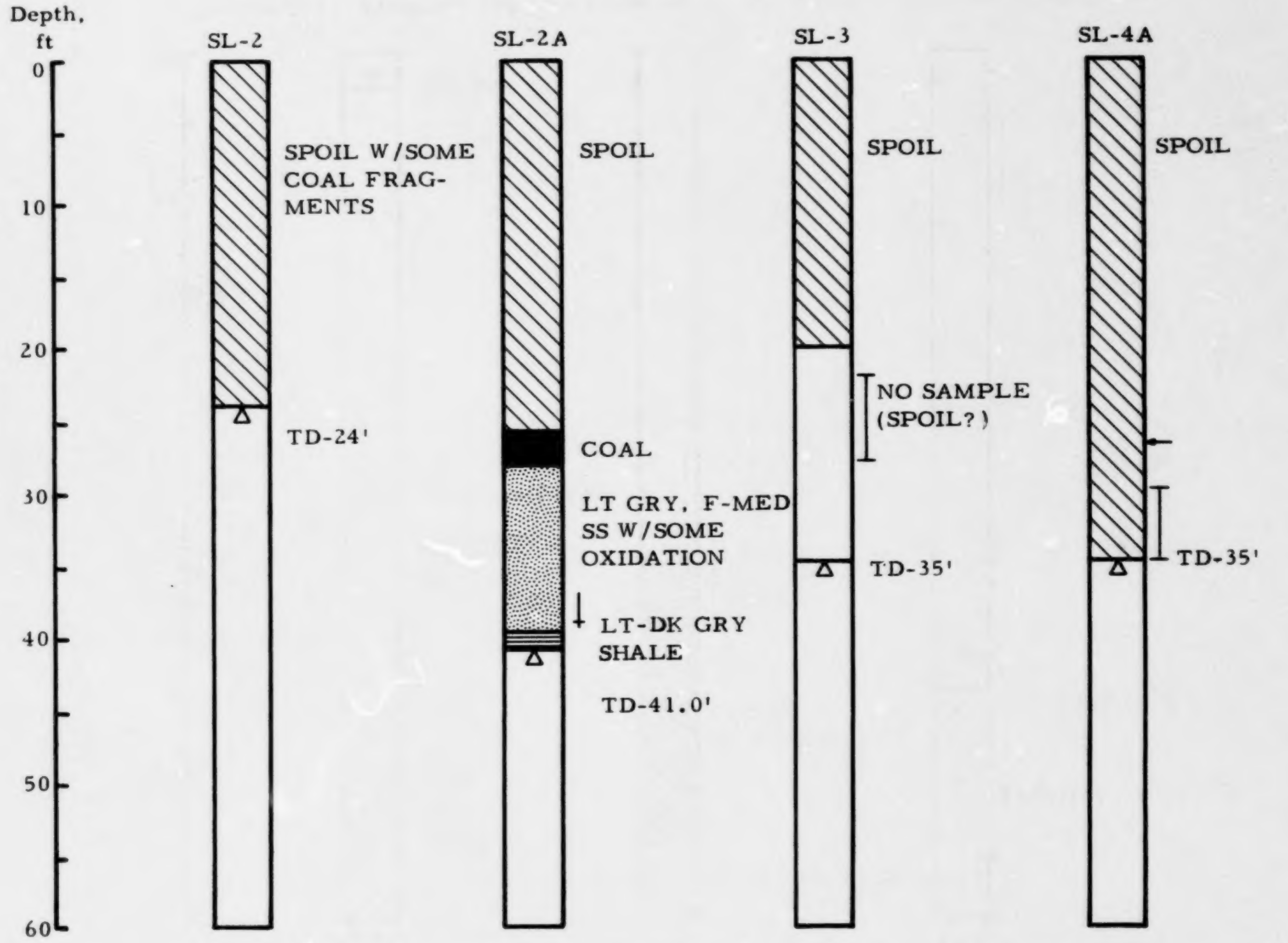


Figure A-2. Field log and hole completion. Edna Mine, Colorado (Cont.).

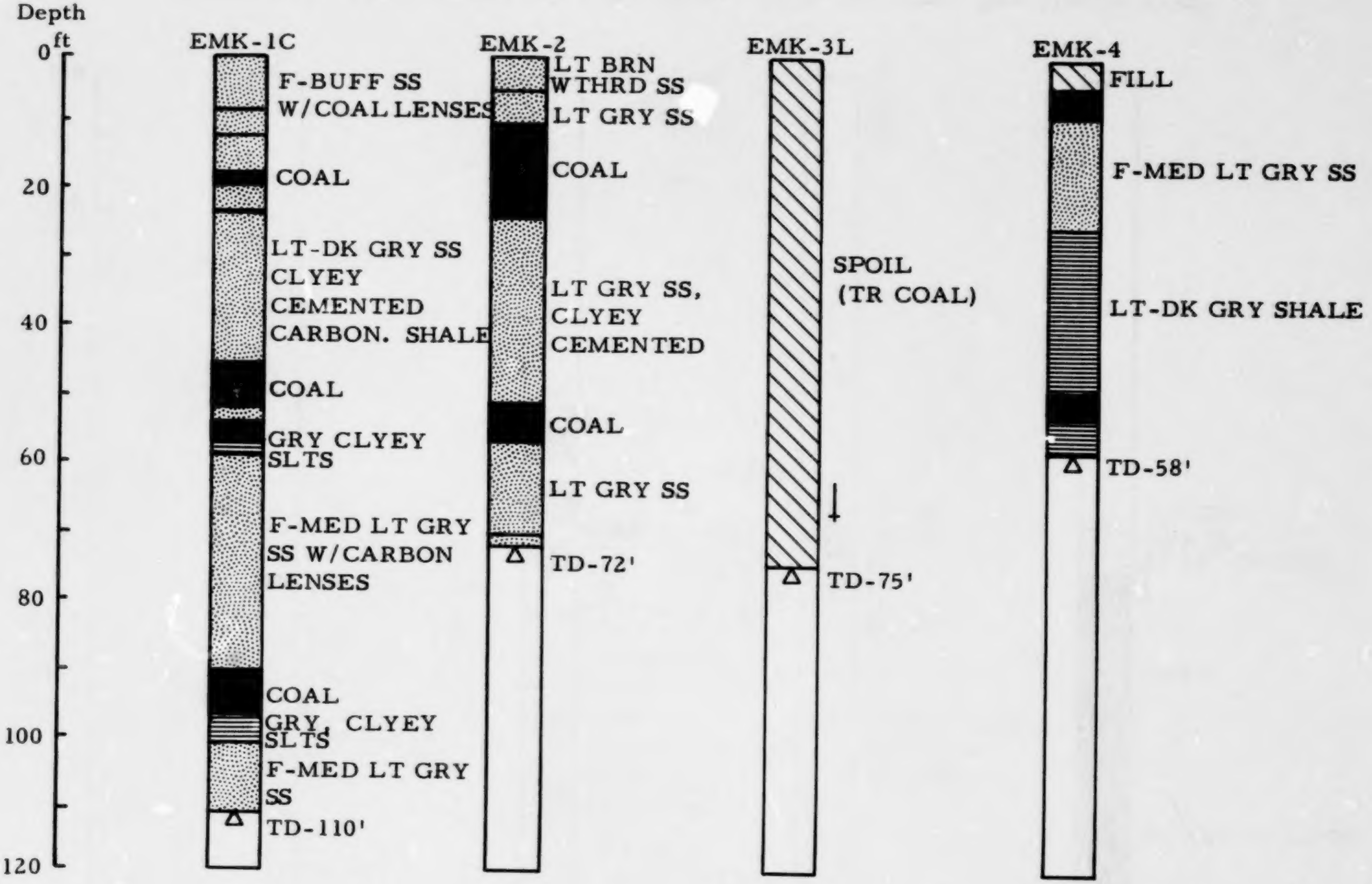

Depth
ft
0
20
40
60
80
100
120
EMK-1C
F-BUFF SS
W/COAL LENSES
COAL
LT-DK GRY SS
CLYEY
CEMENTED
CARBON. SHALE
COAL
GRY CLYEY
SLTS
F-MED LT GRY
SS W/CARBON
LENSES
COAL
GRY, CLYEY
SLTS
F-MED LT GRY
SS
TD-110'
EMK-2
LT BRN
WTHRD SS
LT GRY SS
COAL
LT GRY SS,
CLYEY
CEMENTED
COAL
LT GRY SS
TD-72'
EMK-3L
SPOIL
(TR COAL)
TD-75'
EMK-4
FILL
F-MED LT GRY SS
LT-DK GRY SHALE
TD-58'

Figure A-3. Field log and hole completion. McKinley Mine, New Mexico.

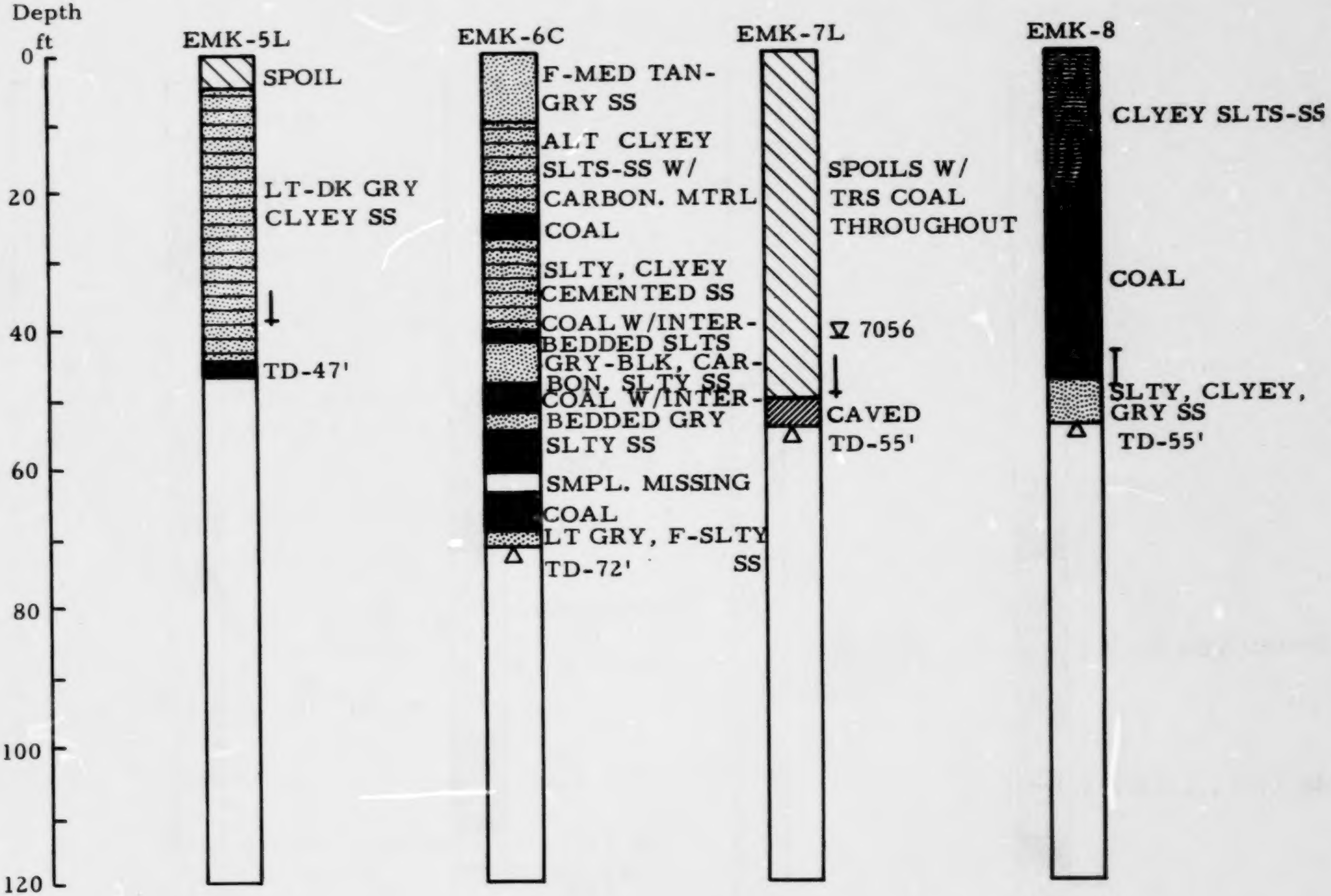

Depth
ft
0
20
40
60
80
100
120
EMK-5L
SPOIL
LT-DK GRY
CLYEY SS
TD-47'
EMK-6C
F-MED TAN-
GRY SS
ALT CLYEY
SLTS-SS W/
CARBON. MTRL
COAL
SLTY, CLYEY
CEMENTED SS
COAL W/INTER-
BEDDED SLTS
GRY-BLK, CAR-
BON. SLTY SS
COAL W/INTER-
BEDDED GRY
SLTY SS
SMPL. MISSING
COAL
LT GRY, F-SLTY
SS
TD-72'
EMK-7L
SPOILS W/
TRS COAL
THROUGHOUT
∇ 7056
CAVED
TD-55'
EMK-8
CLYEY SLTS-SS
COAL
SLTY, CLYEY,
GRY SS
TD-55'

Figure A-3. Field log and hole completion. McKinley Mine, New Mexico (Cont).

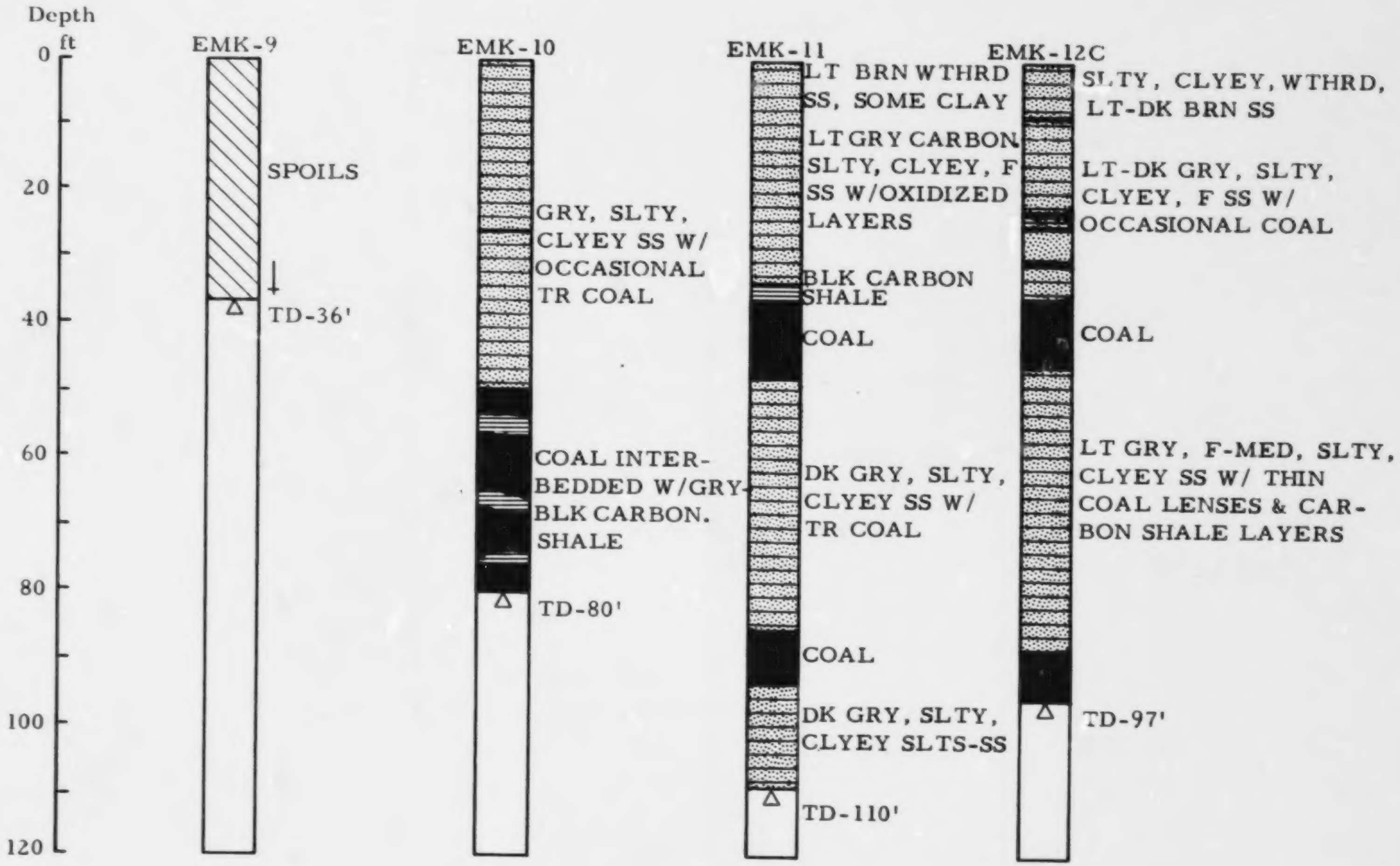

Depth
ft
0
20
40
60
80
100
120
EMK-9
SPOILS
TD-36'
EMK-10
GRY, SLTY, CLYEY SS W/ OCCASIONAL TR COAL
COAL INTER-BEDDED W/GRY-BLK CARBON. SHALE
TD-80'
EMK-11
LT BRN WTHRD SS, SOME CLAY
LT GRY CARBON SLTY, CLYEY, F SS W/OXIDIZED LAYERS
BLK CARBON SHALE
COAL
DK GRY, SLTY, CLYEY SS W/ TR COAL
COAL
DK GRY, SLTY, CLYEY SLTS-SS
TD-110'
EMK-12C
SLTY, CLYEY, WTHRD, LT-DK BRN SS
LT-DK GRY, SLTY, CLYEY, F SS W/ OCCASIONAL COAL
COAL
LT GRY, F-MED, SLTY, CLYEY SS W/ THIN COAL LENSES & CARBON SHALE LAYERS
TD-97'

Figure A-3. Field log and hole completion, McKinley Mine, New Mexico (Cont).

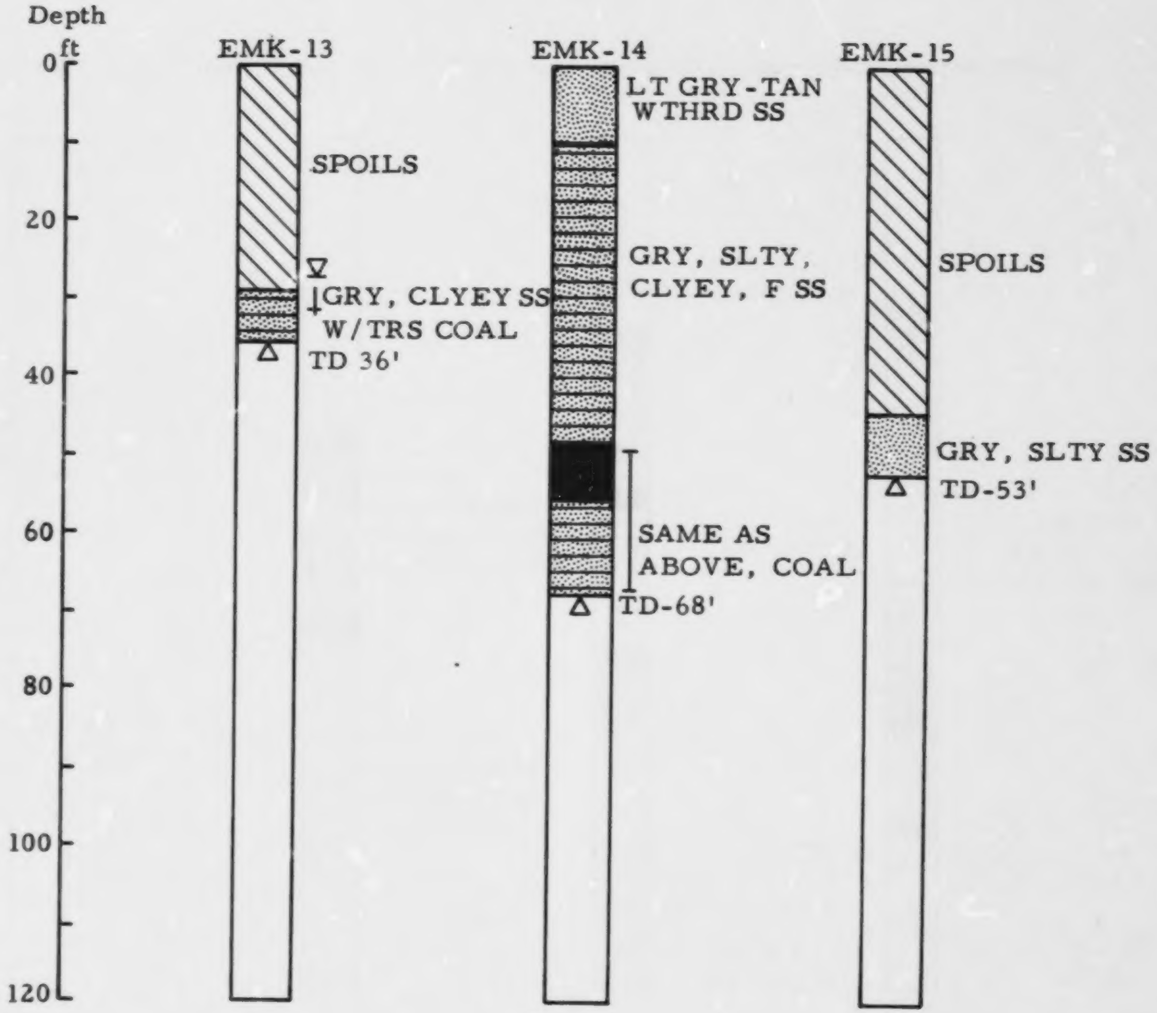

Depth
ft
0
20
40
60
80
100
120
EMK-13
SPOILS
GRY, CLYEY SS
W/TRS COAL
TD 36'
EMK-14
LT GRY-TAN
WTHRD SS
GRY, SLTY,
CLYEY, F SS
SAME AS
ABOVE, COAL
TD-68'
EMK-15
SPOILS
GRY, SLTY SS
TD-53'

Figure A-3. Field log and hole completion. McKinley Mine, New Mexico (Cont).

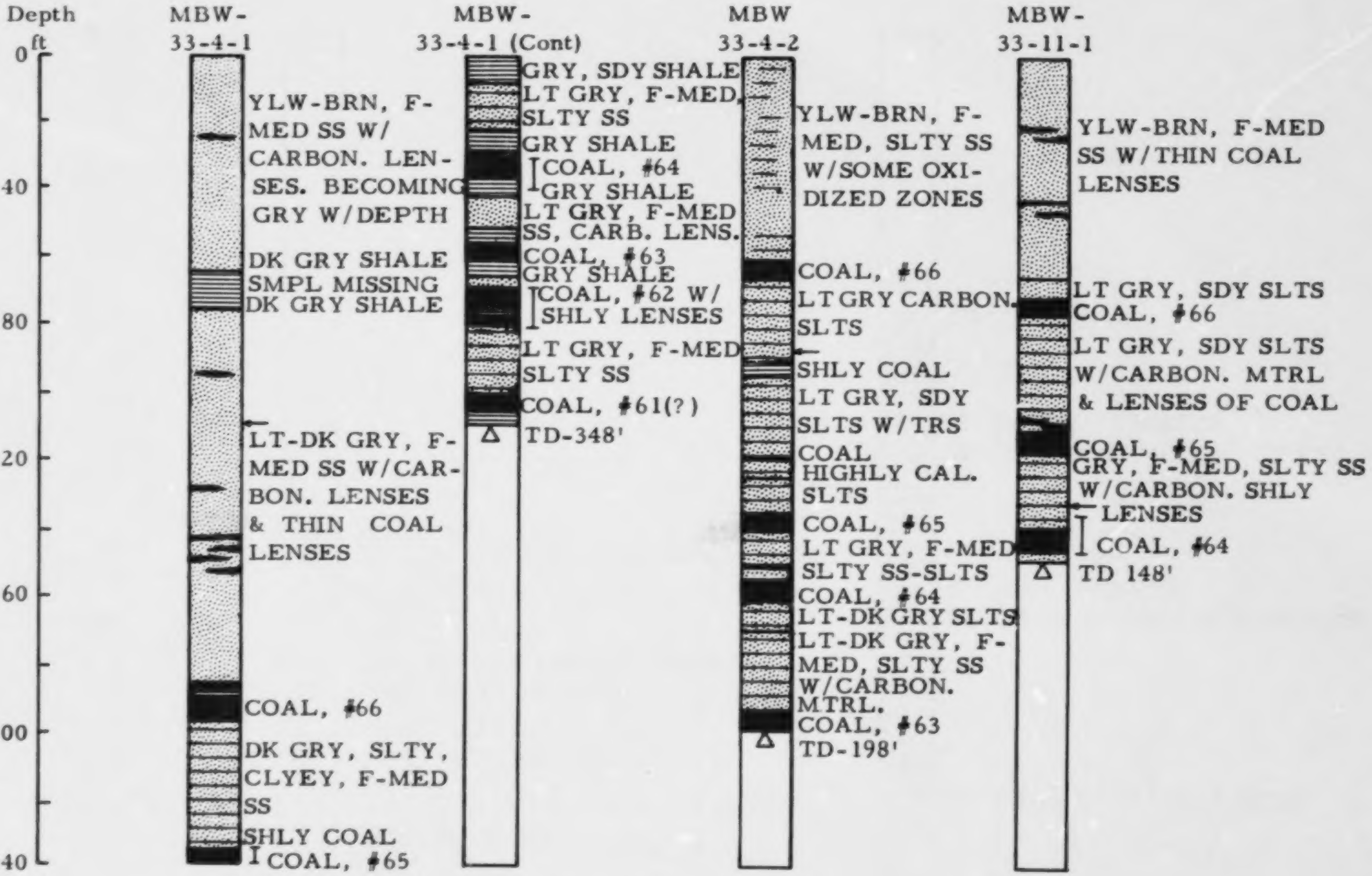

Depth
ft
0
40
80
120
160
200
240
MBW-
33-4-1
YLW-BRN, F-MED SS W/ CARBON. LENSES. BECOMING GRY W/DEPTH
DK GRY SHALE
SMPL MISSING
DK GRY SHALE
LT-DK GRY, F-MED SS W/CARBON. LENSES & THIN COAL LENSES
COAL, #66
DK GRY, SLTY, CLYEY, F-MED SS
SHLY COAL
COAL, #65
MBW-
33-4-1 (Cont)
GRY, SDY SHALE
LT GRY, F-MED, SLTY SS
GRY SHALE
COAL, #64
GRY SHALE
LT GRY, F-MED SS, CARB. LENS.
COAL, #63
GRY SHALE
COAL, #62 W/ SHLY LENSES
LT GRY, F-MED SLTY SS
COAL, #61(?)
TD-348'
MBW
33-4-2
YLW-BRN, F-MED, SLTY SS W/SOME OXIDIZED ZONES
COAL, #66
LT GRY CARBON. SLTS
SHLY COAL
LT GRY, SDY SLTS W/TRS COAL
HIGHLY CAL. SLTS
COAL, #65
LT GRY, F-MED SLTY SS-SLTS
COAL, #64
LT-DK GRY SLTS
LT-DK GRY, F-MED, SLTY SS W/CARBON. MTRL.
COAL, #63
TD-198'
MBW-
33-11-1
YLW-BRN, F-MED SS W/THIN COAL LENSES
LT GRY, SDY SLTS
COAL, #66
LT GRY, SDY SLTS W/CARBON. MTRL & LENSES OF COAL
COAL, #65
GRY, F-MED, SLTY SS W/CARBON. SHLY LENSES
COAL, #64
TD 148'

Figure A-4. Field log and hole completion. Medicine Bow Mine, Wyoming.

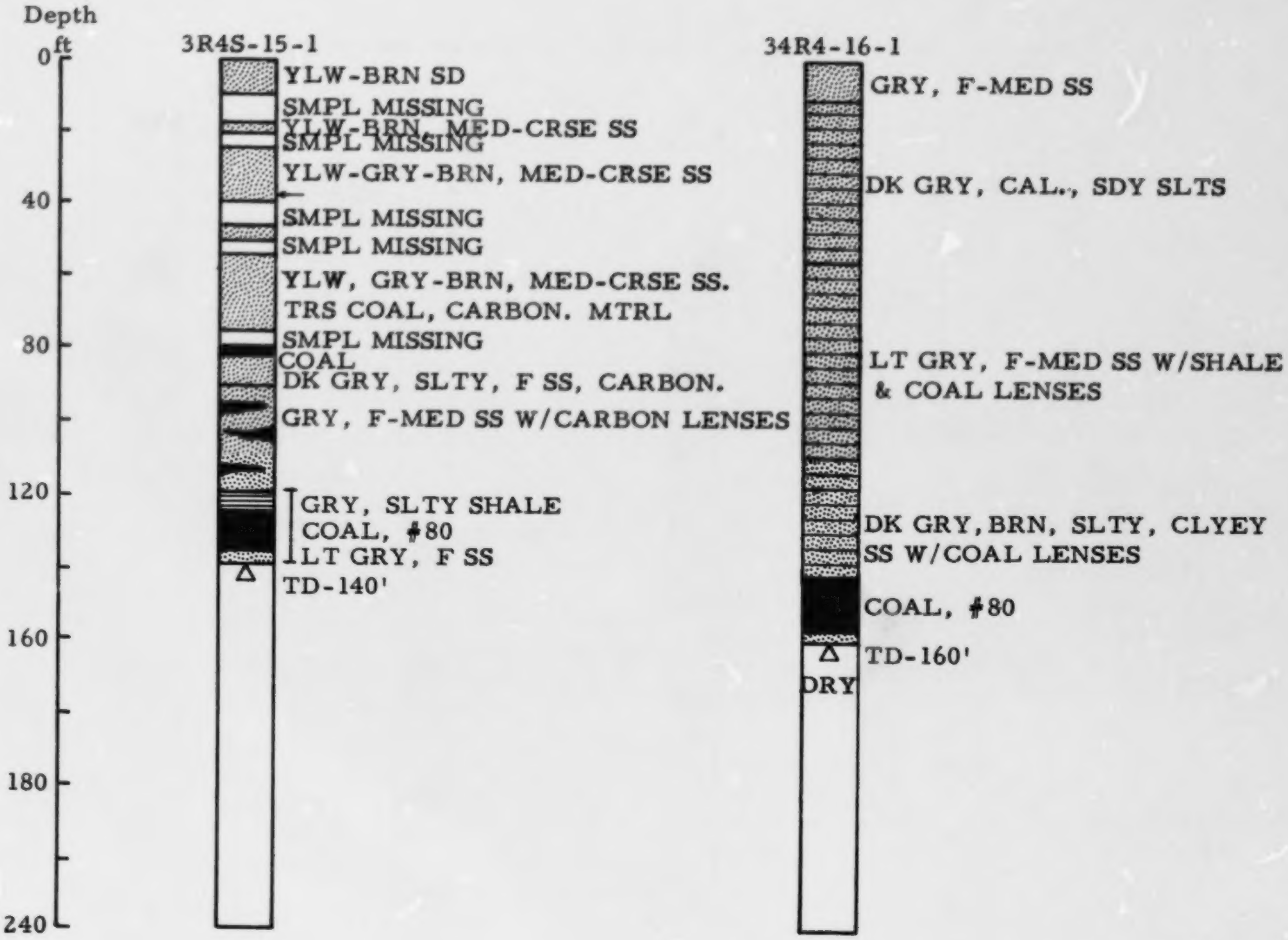

Depth
ft
0
40
80
120
160
180
240
3R4S-15-1
YLW-BRN SD
SMPL MISSING
YLW-BRN, MED-CRSE SS
SMPL MISSING
YLW-GRY-BRN, MED-CRSE SS
SMPL MISSING
SMPL MISSING
YLW, GRY-BRN, MED-CRSE SS.
TRS COAL, CARBON. MTRL
SMPL MISSING
COAL
DK GRY, SLTY, F SS, CARBON.
GRY, F-MED SS W/CARBON LENSES
GRY, SLTY SHALE
COAL, #80
LT GRY, F SS
TD-140'
34R4-16-1
GRY, F-MED SS
DK GRY, CAL., SDY SLTS
LT GRY, F-MED SS W/SHALE & COAL LENSES
DK GRY, BRN, SLTY, CLYEY SS W/COAL LENSES
COAL, #80
TD-160'
DRY

Figure A-5. Field log and hole completion. Rosebud Mine, Wyoming.

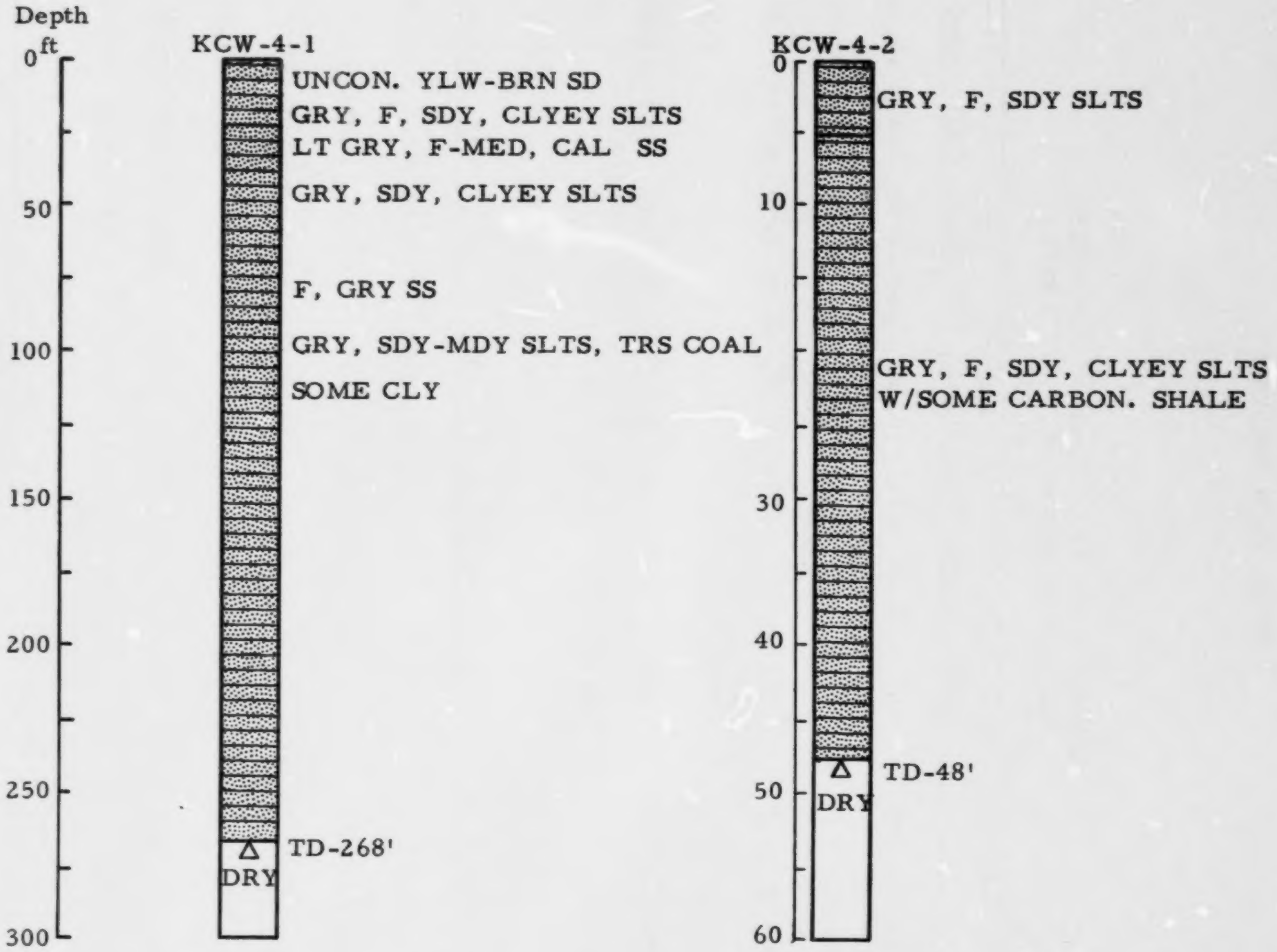

Depth
ft
0
50
100
150
200
250
300
KCW-4-1
UNCON. YLW-BRN SD
GRY, F, SDY, CLYEY SLTS
LT GRY, F-MED, CAL SS
GRY, SDY, CLYEY SLTS
F, GRY SS
GRY, SDY-MDY SLTS, TRS COAL
SOME CLY
TD-268'
DRY
KCW-4-2
0
10
30
40
50
60
GRY, F, SDY SLTS
GRY, F, SDY, CLYEY SLTS
W/SOME CARBON. SHALE
TD-48'
DRY

Figure A-6. Field log and hole completion. Kemmerer Mine, Wyoming.

APPENDIX B

WHOLE ROCK ANALYSES

TABLE B-1. WHOLE ROCK ANALYSES
ENERGY FUELS MINE, COLORADO
(Weight %)

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MgO	CaO	MnO
Core 7A, 13'	81.5	8.04	0.42	0.79	0.60	0.35	0.27	<0.01
Core 7A, 58'	48.0	9.35	0.56	0.03	9.21	3.51	4.53	0.24
Core SL-3, 0'-5'	64.3	10.7	0.59	0.60	2.16	1.56	4.03	0.05
Core SL-3, 25'-30'	72.5	10.5	0.54	0.60	2.29	1.00	1.24	0.04
Core SL-3, 45'-52'	53.4	7.98	0.33	0.43	1.05	1.19	2.90	0.01
Average	63.4	9.73	0.49	0.54	1.83	1.25	2.72	0.03

	K_2O	Na_2O	P_2O_5	SO_4	$S^=$	CO_2	H_2O
Core 7A, 13'	1.61	0.51	0.10	0.06	<0.01	<0.2	2.20
Core 7A, 58'	1.45	0.28	0.15	0.02	0.06	11.5	16.7
Core SL-3, 0'-5'	1.64	0.37	0.14	0.11	0.06	3.9	10.5
Core SL-3, 25'-30'	1.71	0.39	0.13	0.09	0.01	0.9	5.84
Core SL-3, 45'-52'	1.05	0.28	0.10	0.05	0.02	0.6	27.5
Average	1.47	0.35	0.12	0.08	0.03	1.8	14.61

TABLE B-2. WHOLE ROCK ANALYSES
EDNA MINE, COLORADO

(Weight %)

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MgO	CaO	MnO
Core CD-1A, 21'	75.0	11.5	0.63	0.79	0.35	0.31	0.07	<0.01
Core CD-1A, 86'-25'	69.3	14.3	0.72	0.93	0.45	0.77	0.36	<0.01
Core SL-10, 0'-10'	70.4	10.3	0.39	1.60	1.14	0.72	1.67	0.04
Core SL-10, 20'-30'	63.6	8.33	0.25	0.33	1.43	1.44	7.57	0.03
Core SL-10, 60'-70'	64.6	10.3	0.32	0.69	1.26	0.51	2.68	0.02
Average	66.2	9.64	0.32	0.87	1.27	0.89	3.97	0.03
Core SL-12, 0'-10'	62.0	10.9	0.61	0.42	1.49	2.21	3.35	0.04
Core SL-12, 10'-15'	63.5	10.5	0.55	1.20	1.21	1.95	3.31	0.04
Core SL-12, 15'-18'	72.8	8.21	0.45	0.54	1.21	1.66	2.56	0.04
Average	66.1	9.87	0.54	0.72	1.30	1.94	3.07	0.04

	K_2O	Na_2O	P_2O_5	SO_4	$S^=$	CO_2	H_2O
Core CD-1A, 21'	1.98	0.61	0.13	0.21	0.40	0.2	4.75
Core CD-1A, 86'-25'	2.30	0.47	0.10	0.02	0.26	<0.2	7.97
Core SL-10, 0'-10'	1.20	0.78	0.08	0.92	0.07	2.2	7.80
Core SL-10, 20'-30'	0.93	0.88	0.06	0.19	0.07	7.8	11.0
Core SL-10, 60'-70'	0.99	0.70	0.07	0.46	0.26	2.2	15.4
Average	1.04	0.79	0.07	0.52	0.13	4.07	11.4
Core SL-12, 0'-10'	1.61	0.41	0.13	0.05	0.47	5.0	12.6
Core SL-12, 10'-15'	1.69	0.49	0.13	0.13	0.45	3.8	12.3
Core SL-12, 15'-18'	1.49	0.44	0.11	0.05	0.24	2.6	7.8
Average	1.60	0.45	0.12	0.08	0.39	3.8	10.9

TABLE B-3. WHOLE ROCK X-RAY FLUORESCENCE DATA ENERGY FUELS MINE, COLORADO

	Samples				
Elements ppm	CD-7A 13'	CD-7A 58'	SL-3 0-5'	SL-3 25-30'	SL-3 40-52'
Antimony	20	--	--	--	--
Arsenic	--	--	--	--	--
Barium	490	820	720	780	630
Chromium	--	--	--	--	--
Cobalt	--	--	--	--	--
Columbium	--	--	--	--	--
Copper	30	80	70	70	50
Gold	--	--	--	--	--
Iron	6,100	2,300	16,000	17,000	12,000
Lead	140	--	120	--	100
Manganese	260	1,200	620	260	180
Molybdenum	--	20	30	20	--
Nickel	--	20	50	--	40
Niobium	--	40	--	20	20
Rubidium	80	50	80	80	60
Silver	20	--	--	--	--
Strontium	80	120	120	100	200
Thorium	--	--	--	--	--
Tin	--	--	--	--	--
Titanium	1,400	1,300	1,100	1,600	810
Tungsten	--	--	--	--	--
Uranium	--	--	--	--	--
Vanadium	--	230	--	--	--
Yttrium	30	40	30	60	50
Zinc	120	70	90	50	80
Zirconium	360	130	250	400	320

TABLE B-4. WHOLE ROCK X-RAY FLUORESCENCE DATA EDNA MINE, COLORADO

Elements ppm	Samples CD-1 21'	CD-1 86-25'	SL-10 0-10'	SL-10 20-30'	SL-10 60-70'	SL-12 0-5'	SL-12 10-15'	SL-12 15-18'
Antimony	--	--	--	--	70	--	--	--
Arsenic	30	--	30	--	--	40	--	--
Barium	850	740	520	470	400	800	910	650
Chromium	--	--	--	--	--	10	--	--
Cobalt	--	--	10	--	--	--	--	--
Columbium	--	--	--	--	--	--	--	--
Copper	80	40	10	70	80	110	50	20
Gold	--	--	--	--	--	--	--	--
Iron	6,100	6,800	12,000	10,000	12,000	12,000	11,000	8,300
Lead	20	80	80	90	70	90	50	80
Manganese	210	130	400	290	170	260	480	360
Molybdenum	20	20	--	20	--	--	--	20
Nickel	30	10	10	30	10	10	50	10
Niobium	30	--	--	--	--	20	--	--
Rubidium	130	160	80	60	40	130	90	80
Silver	20	50	20	50	40	50	--	--
Strontium	80	110	100	210	140	240	190	80
Tellurium	60	60	--	--	--	--	--	--
Thorium	--	--	--	--	--	110	--	--
Tin	--	--	20	--	20	20	--	40
Titanium	1,300	1,400	1,900	1,300	1,100	1,900	1,600	1,300
Tungsten	--	--	--	--	--	--	--	--
Uranium	--	80	--	--	70	--	--	30
Vanadium	--	300	--	--	--	--	--	300
Yttrium	30	40	30	40	40	50	50	30
Zinc	130	140	70	60	40	130	70	50
Zirconium	480	350	180	150	150	310	270	310

TABLE B-5. WHOLE ROCK
X-RAY FLUORESCENCE DATA
McKINLEY MINE, NEW MEXICO

	Samples											
	1	1	1	1	1	1	1	3	4	7	13	15
Elements	87.28'	18' CA*	47' CA*	50' CA*	96' CA*	74'	101'	65-70'	40-50'	50-55'	30-35'	50-52.3'
Antimony	--	--	--	--	--	--	--	--	--	54	--	--
Arsenic	--	--	33	72	90	24	--	--	--	--	--	43
Barium	740	3,800	14,000	15,000	320	860	990	790	660	430	350	900
Chromium	410	210	--	140	190	--	53	--	--	--	24	--
Cobalt	--	--	--	320	--	--	--	--	--	--	--	--
Columbium	58	96	49	--	--	38	--	41	--	--	--	--
Copper	56	330	300	350	240	110	85	96	95	62	110	96
Gold	--	--	--	--	--	--	--	--	--	--	--	--
Iron	74,000	85,000	19,000	76,000	23,000	7,900	31,000	20,000	21,000	13,000	14,000	11,000
Lead	--	88	150	260	210	66	--	--	96	21	64	--
Manganese	3,700	200	170	190	430	310	810	330	370	370	220	330
Molybdenum	12	42	--	51	30	--	--	--	--	--	--	16
Nickel	--	560	220	540	240	--	84	62	18	18	150	20
Rubidium	60	--	27	110	130	130	60	140	84	110	140	150
Silver	--	--	--	--	--	--	--	--	--	75	--	--
Strontium	130	1,700	1,500	2,900	2,400	110	230	230	200	260	230	160
Thorium	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	490	1,400	--	1,600	1,600	2,600	660	1,600	2,600	1,900	2,300	1,300
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	150	--	--	--	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--	--	--
Yttrium	47	230	110	300	110	54	30	55	54	42	84	42
Zinc	110	140	150	130	160	60	120	240	74	130	100	54
Zirconium	130	340	730	--	120	270	230	350	210	230	190	220

* CA = Coal Ash.

TABLE B-5. WHOLE ROCK
X-RAY FLUORESCENCE DATA (Cont.)
McKINLEY MINE, NEW MEXICO

	Samples												
Elements	**Pit 32**	**Pit 34**	**2 35-40'**	**4 20-25'**	**6 55'**	**6 70'**	**8 30-35'**	**11 70-75'**	**12 80-85'**	**12 72'**	**12 74'**	**14 45-50'**	**14 55-60'**
Antimony	--	--	--	--	--	--	--	38	42	--	--	--	--
Arsenic	27	--	49	28	--	--	--	--	--	--	--	--	--
Barium	810	960	1,600	1,300	700	800	580	1,100	540	900	800	400	790
Chromium	--	53	--	--	--	--	--	53	--	210	--	--	--
Cobalt	--	--	--	--	--	--	13	--	--	--	--	--	--
Columbium	--	--	--	54	--	45	47	--	--	30	--	17	--
Copper	110	39	81	140	100	88	180	140	90	23	110	140	170
Gold	--	35	--	--	--	--	--	--	--	--	--	--	--
Iron	13,000	14,000	14,000	18,000	17,000	6,700	11,000	58,000	21,000	12,000	13,000	5,500	12,000
Lead	--	200	110	31	81	22	--	--	--	78	110	56	66
Manganese	290	220	310	240	170	130	44	1,400	180	330	420	150	88
Molybdenum	--	--	--	--	--	--	--	--	--	24	--	--	--
Nickel	50	40	73	84	90	50	20	49	110	38	47	--	34
Rubidium	140	140	220	130	98	130	120	84	140	140	98	110	250
Silver	--	--	--	--	--	--	--	34	--	--	--	--	--
Strontium	200	180	170	200	290	130	320	160	230	180	160	97	240
Thorium	--	--	--	--	--	--	--	38	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	50	--	--
Titanium	1,600	1,100	1,600	1,500	2,100	1,800	1,500	1,500	1,500	2,000	1,900	1,100	2,300
Tungsten	--	--	--	--	--	--	--	--	--	--	150	--	--
Uranium	--	--	--	--	--	25	--	--	--	--	--	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--	--	--	--
Yttrium	43	57	84	48	40	63	37	62	65	30	40	40	76
Zinc	140	150	180	140	90	230	150	270	160	81	130	110	150
Zirconium	350	240	400	310	220	460	190	270	290	230	190	170	270

TABLE B-6. WHOLE ROCK
X-RAY FLUORESCENCE DATA
MEDICINE BOW MINE, WYOMING

	Samples																
Elements	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 66	S3B	Well 33-4-2 75-80'	Well 33-4-2 85-90'	Well 33-4-2 95-100'	Well 33-4-2 47.5'	Well 33-11-1 59'	Well 33-11-1 69'	Well 33-11-1 123'	Soil No. 31	Soil No. 32	Lake (Seminoe Reservoir)
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	27	17	--	--	--	--	17	--	--	--	23	--	130	--	--	--	--
Barium	970	1,100	570	1,100	880	1,000	1,000	320	490	580	800	1,100	580	540	640	650	840
Chromium	70	--	--	--	--	96	--	--	--	--	--	--	--	--	--	--	10
Cobalt	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Columbium	21	34	25	--	--	12	28	23	38	--	--	--	21	--	9	--	13
Copper	130	130	180	75	120	70	95	88	34	20	36	96	130	30	72	77	96
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	18,000	15,000	17,000	30,000	16,000	22,000	9,400	11,000	14,000	10,000	5,700	11,000	19,000	9,300	7,000	18,000	30,000
Lead	87	28	110	74	--	--	--	--	--	120	37	120	78	46	20	--	130
Manganese	330	440	480	350	440	510	440	460	400	340	62	370	180	290	400	480	690
Molybdenum	70	--	--	--	25	--	--	--	--	--	--	--	9	8	7	--	--
Nickel	80	50	180	60	70	62	10	40	--	--	--	20	--	--	--	10	60
Rubidium	170	42	140	250	98	110	21	130	90	140	90	140	200	120	60	180	170
Selenium	--	--	--	--	--	--	--	--	--	--	29	--	--	--	--	--	--
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	320	430	830	280	190	180	83	140	140	140	58	72	150	110	88	170	140
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	1,500	1,100	1,300	1,800	1,600	1,800	810	1,400	1,400	470	950	810	1,300	1,100	1,300	810	830
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vanadium	--	76	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Yttrium	69	46	26	57	69	81	21	48	38	37	30	46	50	72	31	21	75
Zinc	150	130	150	240	150	73	44	90	19	110	72	110	42	140	36	8	84
Zirconium	250	370	430	180	310	300	230	230	420	160	120	590	190	250	250	220	320

TABLE B-7. WHOLE ROCK
X-RAY FLUORESCENCE DATA
ROSEBUD MINE, WYOMING

Elements	Samples																		
	Nugget										Well 34R4-16-1				Well 3R4S-15-1				
	R4-N1	R4-N2	R4-N3	R4-N4	Pond 1	Pond 4	Pit 4	Pit 4S	R-1	R-2	5-10'	80-85'	125-130'	150-155'	27'	73'	115.9'	Top Profile No. 33	Groundhog No. 35
Antimony	--	--	70	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	--	19	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Barium	810	920	1,100	580	960	880	580	580	700	650	500	730	530	210	1,300	910	790	960	700
Chromium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cobalt	--	--	--	--	--	--	--	--	--	--	--	9	--	--	--	--	--	--	--
Columbium	--	23	--	40	--	50	--	--	--	--	--	--	19	--	--	--	18	52	21
Copper	120	110	11,000	40	50	50	90	40	100	58	52	44	10	35	37	84	36	55	92
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	21,000	23,000	23,000	47,000	13,000	19,000	15,000	16,000	12,000	13,000	25,000	7,100	13,000	8,000	6,600	2,200	10,000	1,500	15,000
Lead	--	140	--	90	70	50	--	--	110	87	58	130	75	69	68	46	93	81	100
Manganese	44	400	290	550	350	340	180	350	420	330	1,000	400	130	270	130	320	440	330	400
Molybdenum	--	--	--	--	--	--	--	--	--	--	--	6	--	9	--	13	21	--	--
Nickel	65	74	60	60	30	10	20	50	50	40	50	10	--	--	--	--	--	11	11
Rubidium	120	200	120	130	100	100	120	140	120	140	110	60	110	48	66	46	66	180	150
Silver	--	--	30	--	--	--	--	30	--	--	--	--	--	--	--	--	--	--	--
Strontium	210	270	90	230	240	220	320	330	99	150	280	64	230	380	190	180	99	220	200
Thorium	--	--	--	--	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	1,800	1,100	1,300	1,800	1,400	1,800	810	1,800	1,500	650	1,500	950	1,700	950	--	470	950	1,600	1,800
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	21	--	--	--	--	--	30	--
Vanadium	--	76	80	80	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Yttrium	20	38	10	70	30	20	80	30	32	77	55	31	47	28	18	22	44	75	32
Zinc	190	200	120	140	70	140	160	80	60	54	120	50	140	84	30	49	42	100	130
Zirconium	210	340	360	250	260	150	220	370	130	440	320	180	160	68	140	94	280	330	280

TABLE B-8. WHOLE ROCK
X-RAY FLUORESCENCE DATA
KEMMERER MINE, WYOMING

	Samples																		
Elements	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	26	--	--	--
Arsenic	34	58	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Barium	560	630	1,000	210	190	200	1,900	370	280	390	170	470	560	370	1,300	800	960	540	190
Chromium	--	--	--	--	--	--	--	--	--	--	46	68	24	--	--	--	86	--	30
Cobalt	12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	--	--
Columbium	--	22	11	--	29	--	38	--	76	--	--	--	--	21	--	--	--	--	--
Copper	77	130	81	99	72	21	240	40	94	67	46	84	48	65	160	110	72	48	39
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	17,000	15,000	23,000	15,000	11,000	19,000	30,000	21,000	21,000	16,000	130,000	140,000	13,000	17,000	20,000	15,000	16,000	21,000	18,000
Lead	25	35	120	84	84	66	78	200	64	87	--	--	56	74	88	78	150	160	140
Manganese	640	220	1,100	230	190	130	120	460	260	340	74	150	270	90	900	290	920	620	310
Molybdenum	--	--	34	--	--	--	--	--	--	--	--	38	--	--	--	--	--	--	15
Nickel	12	40	18	--	--	18	28	62	51	29	130	260	18	70	65	--	80	110	20
Rubidium	100	140	150	130	28	69	60	180	160	160	74	--	110	150	84	70	88	130	98
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	25	--	--	--
Strontium	82	250	130	130	87	100	600	250	380	340	26	87	130	160	120	150	160	200	130
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	810	1,700	1,500	980	1,800	1,500	1,300	1,500	820	1,500	890	1,700	820	1,800	640	1,900	1,400	1,200	1,100
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--	140	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--	--	--	380	--	--	--	--	--	--
Yttrium	29	72	72	44	36	33	98	49	81	46	--	87	44	49	--	31	60	38	38
Zinc	96	180	140	94	110	95	160	130	90	180	110	110	88	140	90	150	760	120	72
Zirconium	260	300	--	150	90	130	490	310	310	290	110	160	710	400	250	310	200	340	160

TABLE B-9. WHOLE ROCK X-RAY FLUORESCENCE DATA WYODAK MINE, WYOMING

Elements	Samples 2	3	4	5	7
Antimony	--	--	--	--	--
Arsenic	17	--	26	9	45
Barium	1,700	1,300	860	600	400
Chromium	--	--	--	--	--
Cobalt	--	--	--	24	--
Columbium	--	--	--	--	15
Copper	140	78	120	120	160
Gold	--	--	--	--	--
Iron	12,000	29,000	14,000	39,000	20,000
Lead	160	96	27	84	18
Manganese	310	640	350	130	260
Molybdenum	15	--	--	--	11
Nickel	34	51	11	80	--
Rubidium	110	140	150	84	28
Silver	--	--	--	--	--
Strontium	290	170	290	190	540
Tellurium	--	--	--	--	--
Thorium	--	--	--	--	--
Tin	--	--	--	--	--
Titanium	1,100	1,100	1,500	970	1,300
Tungsten	--	--	--	--	--
Uranium	--	--	--	--	--
Vanadium	--	--	--	--	--
Yttrium	58	58	73	50	37
Zinc	81	230	81	140	170
Zirconium	210	220	250	150	110

TABLE B-10. WHOLE ROCK X-RAY FLUORESCENCE DATA COLSTRIP MINE, MONTANA

Elements	Samples									
	1	2	6A	7	7A	8	10	13	14	15
Antimony	--	--	--	--	--	--	--	--	--	--
Arsenic	10	20	43	17	--	17	54	21	25	9
Barium	620	--	620	370	750	580	4,800	470	660	440
Chromium	--	--	--	50	--	--	62	--	--	--
Cobalt	--	--	--	--	--	--	--	--	--	--
Columbium	--	--	--	--	--	11	--	40	--	--
Copper	94	20	60	39	90	57	140	84	78	40
Gold	--	--	--	--	--	--	--	--	--	--
Iron	30,000	5,000	110,000	19,000	39,000	10,000	210,000	46,000	8,900	9,700
Lead	110	35	290	--	140	--	--	170	24	150
Manganese	440	330	150	200	410	180	960	210	350	660
Molybdenum	18	9	18	--	--	9	19	--	--	--
Nickel	20	--	210	30	26	20	150	--	24	--
Rubidium	64	--	--	68	76	54	--	80	96	52
Silver	--	--	--	--	--	--	--	--	--	--
Strontium	100	540	48	260	200	480	24	93	93	100
Thorium	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--
Titanium	970	950	330	1,500	1,300	1,300	1,400	1,300	800	1,600
Tungsten	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	50
Vanadium	--	--	--	--	--	--	--	--	--	--
Yttrium	37	21	--	52	40	32	27	30	45	38
Zinc	38	20	60	110	100	38	63	57	22	22
Zirconium	220	100	170	210	230	190	210	170	180	580
Iodine	--	--	--	84	--	--	--	--	--	--

TABLE B-11. CLAY FRACTION
X-RAY FLUORESCENCE DATA
ENERGY FUELS MINE, COLORADO

Elements	Samples																	
	CD-7A 13'	CD-7A 18'	CD-7A 21'	CD-7A 28'	CD-7A 29'	CD-7A 36'	CD-7A 42'	CD-7A 50'	CD-7A 53'	CD-7A 58'	CD-7A 64'	CD-7A 77'	CD-7A 82'	SL-1B 0-5'	SL-1B 35-40'	SL-3 0-5'	SL-3 25-30'	SL-3 45-52'
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Barium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chromium	540	600	630	510	700	330	580	400	330	540	--	120	390	800	670	400	470	670
Cobalt	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Columbium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Copper	150	90	100	30	80	80	120	30	140	120	100	80	210	--	99	110	--	150
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	43,000	71,000	21,000	17,000	110,000	26,000	32,000	29,000	36,000	51,000	17,000	11,000	91,000	33,000	74,000	64,000	69,000	67,000
Lead	--	--	--	130	330	--	--	--	--	160	--	--	--	--	530	--	--	--
Manganese	270	420	160	290	2,100	160	390	510	320	680	160	150	1,500	280	500	340	460	420
Molybdenum	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Nickel	230	470	150	270	180	390	290	260	330	230	150	180	30	290	430	260	320	270
Rubidium	--	--	--	--	140	--	--	--	--	--	--	--	130	--	--	--	--	--
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	--	--	--	--	70	--	--	--	--	--	--	--	120	--	--	--	--	--
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	1,200	2,100	1,400	1,200	1,200	1,800	1,800	2,000	2,000	1,100	1,100	1,400	2,000	1,200	1,200	890	1,600	1,400
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Yttrium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	84
Zinc	270	280	140	150	200	130	160	180	180	150	180	190	330	470	210	250	430	360
Zirconium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

TABLE B-11. CLAY FRACTION
X-RAY FLUORESCENCE DATA (Cont.)
ENERGY FUELS MINE, COLORADO

	Samples												
Elements	SL-4 0-10'	SL-4 30-31'	D-6 0-5'	D-6 95-100'	D-5 0-5'	D-5 95-100'	D-5 200-205'	D-5 300-305'	D-9 0-5'	D-9 45-50'	D-9 95-100'	D-9 145-150'	D-9 171-175'
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	--	--	--	--	66	--	--	--	--	--	--	--	--
Barium	--	--	--	--	--	--	--	--	520	560	480	--	--
Chromium	730	340	540	340	540	800	800	210	470	330	270	540	540
Cobalt	--	--	--	--	--	--	--	--	--	--	--	--	--
Columbium	--	--	--	--	--	--	--	--	--	30	--	--	--
Copper	--	--	--	--	120	--	140	33	190	200	60	210	150
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	42,000	14,000	59,000	25,000	110,000	43,000	56,000	16,000	95,000	88,000	75,000	58,000	34,000
Lead	--	--	--	--	--	--	--	240	350	480	--	390	--
Manganese	340	480	140	130	1,100	350	360	310	420	490	180	220	250
Molybdenum	--	--	--	--	--	--	--	--	30	--	--	--	--
Nickel	590	260	230	260	270	150	260	260	340	310	360	350	230
Rubidium	--	110	--	--	--	--	--	--	170	260	240	--	60
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	42	110	32	110	--	96	58	120	160	250	260	170	80
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	1,600	1,200	1,100	2,100	710	1,200	1,400	1,200	1,800	1,400	1,600	1,600	1,200
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	60	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--	250	--	--
Yttrium	--	--	--	--	--	--	--	--	140	140	110	--	--
Zinc	360	330	220	160	460	130	220	390	790	330	380	300	210
Zirconium	--	--	--	--	--	--	--	--	170	200	190	80	140

TABLE B-12. CLAY FRACTION
X-RAY FLUORESCENCE DATA
EDNA MINE, COLORADO

Elements	Samples CD-1A 21'	 CD-1A 86-25'	 S-10 0-10'	 S-10 20-30'	 S-10 60-70'	 SL-12 0-5'	 SL-12 10-15'	 SL-12 15-18'
Antimony	--	--	--	--	--	--	--	--
Arsenic	--	70	--	--	--	--	--	--
Barium	--	--	--	--	--	--	--	--
Chromium	340	50	270	270	340	270	400	270
Cobalt	--	--	--	--	--	--	--	--
Columbium	--	90	--	--	--	--	--	--
Copper	30	90	60	30	120	30	130	60
Gold	--	--	--	--	--	--	--	--
Iron	6,800	27,000	15,000	37,000	21,000	22,000	17,000	13,000
Lead	350	--	--	--	700	--	--	--
Manganese	--	180	230	310	220	220	280	280
Molybdenum	60	--	--	--	--	--	--	--
Nickel	230	240	240	150	130	130	160	130
Niobium	--	90	--	--	--	--	--	--
Rubidium	--	170	--	--	--	--	--	--
Silver	--	--	--	--	--	--	--	--
Strontium	120	140	--	40	--	--	--	--
Thorium	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--
Titanium	710	1,800	530	1,100	1,200	1,200	1,200	890
Tungsten	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--
Vanadium	--	--	--	--	--	--	--	--
Yttrium	50	--	--	--	--	--	--	--
Zinc	90	270	210	210	200	360	250	190
Zirconium	140	160	--	--	--	--	--	--

TABLE B-13. CLAY FRACTION
X-RAY FLUORESCENCE DATA
McKINLEY MINE, NEW MEXICO

	Samples													
Elements	Hole 1 18'-CA	Hole 1 47'-CA	Hole 1 50'-CA	Hole 1 96'-CA	Hole 1 16'	Hole 1 22'	Hole 1 74'	Hole 1 101'	Hole 1 Pit 32	Hole 1 Pit 34	Hole 2 35-40'	Hole 3 65-70'	Hole 4 20-25'	Hole 5 40-45'
Antimony	--	--	--		--	--	--	--	--	--	--	--	--	--
Arsenic	--	33	72	90	--	--	--	--	--	--	--	--	--	--
Barium	3,800	14,000	15,000	320	--	--	--	--	--	--	--	700	--	--
Chromium	210	--	140	190	--	160	--	--	--	94	--	120	14	120
Cobalt	--	--	320	--	--	--	--	--	--	--	--	--	--	--
Columbium	96	49	--	--	--	--	--	--	--	--	--	--	--	--
Copper	330	300	350	240	56	75	90	75	140	100	75	44	25	200
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	85,000	19,000	76,000	23,000	17,000	48,000	13,000	20,000	33,000	24,000	19,000	48,000	37,000	38,000
Lead	88	150	260	210	--	440	290	--	--	--	330	330	--	--
Manganese	200	170	190	430	78	280	--	180	200	130	150	100	180	150
Molybdenum	42	--	51	30	66	--	--	43	--	--	120	--	--	--
Nickel	560	220	540	240	100	260	330	55	130	210	160	240	180	130
Rubidium	--	27	110	130	--	37	--	--	--	--	--	130	--	--
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	1,700	1,500	2,900	2,400	--	100	--	--	64	68	64	150	--	--
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	1,400	1,700	1,600	1,600	1,100	1,600	2,000	1,600	1,800	1,100	2,100	2,100	1,600	2,400
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vanadium	--	--	--	--	330	--	--	--	--	--	--	--	--	--
Yttrium	230	110	300	110	78	84	--	--	--	--	--	--	--	--
Zinc	140	150	130	160	300	200	160	130	170	150	160	150	210	210
Zirconium	340	730	600	120	--	120	110	--	100	46	--	140	90	--

TABLE B-13. CLAY FRACTION
X-RAY FLUORESCENCE DATA (Cont.)
McKINLEY MINE, NEW MEXICO

	Samples													
Elements	Hole 6 55'	Hole 6 70'	Hole 7 50-55'	Hole 8 30-36'	Hole 11 70-75'	Hole 11 80-85'	Hole 12 72'	Hole 12 74'	Hole 13 30-35'	Hole 14 45-50'	Hole 14 56-60'	Hole 14 50-52.5'	Hole 1 87.28'	Hole 6 77'
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Barium	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chromium	--	180	--	86	330	--	--	--	--	--	--	100	200	540
Cobalt	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Columbium	--	--	--	--	--	--	110	--	--	70	--	--	--	--
Copper	84	56	25	120	23	28	56	28	28	110	120	23	360	200
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	16,000	14,000	21,000	27,000	18,000	26,000	9,000	10,000	28,000	9,400	29,000	19,000	21,000	2,500
Lead	--	--	--	88	360	440	290	--	110	440	330	--	--	480
Manganese	100	75	180	130	200	--	100	100	130	50	75	160	110	130
Molybdenum	--	--	--	--	--	--	80	--	50	--	54	--	33	40
Nickel	210	260	240	180	80	130	150	80	240	130	180	210	230	250
Rubidium	--	--	--	--	--	--	--	--	40	--	170	--	--	140
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	--	--	110	120	110	--	--	--	120	--	58	72	120	84
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	--	1,800	1,100	2,000	890	1,400	1,400	1,000	1,700	1,100	2,300	1,100	2,100	2,300
Tungsten	--	--	--	--	--	--	--	--	--	--	---	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--	--	--	--	180
Yttrium	--	--	--	--	--	--	92	--	35	--	--	140	--	--
Zinc	220	140	180	190	120	150	160	140	230	140	180	130	200	200
Zirconium	--	--	120	56	--	--	92	--	140	--	160	--	140	210

TABLE B-14. CLAY FRACTION
X-RAY FLUORESCENCE DATA
MEDICINE BOW MINE, WYOMING

	Samples															
Elements	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 66	Soil from 33-4-2 31	Topsoil from Stockpile East of Main Haul Road 32	Hole 33-4-2 75-80'	Hole 33-4-2 85-90'	Hole 33-4-2 95-100'	Hole 33-11-1 47.5'	Hole 33-11-1 59'	Hole 33-11-1 69'	S3B	Lake (Seminoe Reservoir)
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Barium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chromium	280	--	270	230	500	14	330	230	340	210	270	270	210	400	540	340
Cobalt	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Columbium	--	81	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Copper	140	100	100	200	280	260	25	23	370	330	230	260	180	370	210	300
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	62,000	69,000	24,000	81,000	67,000	75,000	29,000	41,000	44,000	32,000	41,000	58,000	35,000	35,000	44,000	86,000
Lead	88	--	300	300	300	530	--	--	48	350	--	290	180	580	480	480
Manganese	500	620	280	470	480	550	350	400	190	250	220	1,000	53	110	920	700
Molybdenum	--	--	--	--	--	--	--	--	74	43	--	--	120	--	--	--
Nickel	290	240	150	330	260	230	230	130	340	340	200	380	480	160	160	250
Rubidium	230	94	--	360	--	--	--	--	--	--	130	160	58	210	110	--
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	170	260	96	310	130	110	--	27	140	46	78	180	84	84	120	110
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	2,000	1,700	1,600	1,700	1,500	1,800	870	1,600	1,600	1,200	1,400	710	1,100	890	1,100	1,200
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	160	--	--	--	--	--
Vanadium	--	--	--	--	340	--	--	--	--	--	--	--	--	--	--	--
Yttrium	160	35	--	180	140	--	--	--	110	--	--	110	--	110	--	180
Zinc	230	390	140	630	400	560	170	150	320	260	400	330	330	320	330	390
Zirconium	140	120	--	180	84	78	--	140	50	--	92	--	--	92	180	200

TABLE B-15. CLAY FRACTION
X-RAY FLUORESCENCE DATA
ROSEBUD MINE, WYOMING

	Samples															
										Nugget				Hole 3R4S-15-1		
Elements	Hole 34R4-16-1 5-10'	Hole 34R4-16-1 80-85'	Hole 34R4-16-1 125-130'	R-1	R-2	Pit 4	Pit 4S	Pond 1	Pond 4	N1	N2	N3	N4	27'	73'	115.9'
Antimony	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arsenic	--	--	60	--	54	--	--	--	--	--	--	--	36	--	--	--
Barium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chromium	--	380	330	--	--	470	540	270	140	540	--	470	670	210	210	510
Cobalt	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Columbium	--	96	--	--	--	--	60	--	--	--	270	--	--	--	--	--
Copper	130	120	150	60	190	37	130	150	200	110	110	250	150	50	46	46
Gold	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Iron	16,000	63,000	53,000	6,600	40,000	79,000	76,000	88,000	16,000	95,000	66,000	14,000	85,000	47,000	18,000	33,000
Lead	--	95	100	--	--	530	360	130	130	130	290	350	--	--	160	290
Manganese	180	480	180	160	280	590	500	530	340	170	340	450	480	150	440	420
Molybdenum	--	--	--	--	--	93	28	66	--	66	60	--	--	--	--	--
Nickel	150	330	230	230	380	650	310	430	430	370	430	430	470	210	180	210
Rubidium	--	100	260	--	--	280	160	470	110	--	110	210	170	--	--	--
Silver	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Strontium	39	220	240	78	84	230	140	120	180	36	220	170	180	--	78	46
Thorium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	--	2,100	2,100	360	890	1,100	2,000	1,200	1,400	1,100	1,800	1,400	1,500	1,100	1,000	1,700
Tungsten	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vanadium	--	--	--	--	180	--	--	--	350	91	270	--	--	--	--	--
Yttrium	--	130	36	--	--	--	--	--	180	--	--	--	130	--	58	--
Zinc	69	350	430	180	320	430	180	430	270	290	360	430	660	150	110	130
Zirconium	140	230	100	--	--	120	120	180	74	140	--	--	130	--	120	--

TABLE B-16. CLAY FRACTION
X-RAY FLUORESCENCE DATA
COLSTRIP MINE, MONTANA

Elements	Section E Sandstone in Overburden	Overburden Sandstone Concretion	Spoils		Area E Encrustation	Iron-Rich Sandstone	Iron-Stained Fragment from Spoils	Area D Spoils	
			7	7A				14	15
Antimony	--	--	--	--	--	--	--	--	--
Arsenic	90	95	--	72	80	--	--	--	--
Barium	--	--	--	--	--	--	--	--	--
Chromium	540	210	210	330	200	800	340	230	240
Cobalt	--	--	--	--	--	--	--	--	--
Columbium	130	--	--	--	--	--	--	--	--
Copper	200	28	140	30	60	37	120	66	66
Gold	--	--	--	--	--	--	--	--	--
Iron	24,000	7,500	82,000	53,000	7,600	150,000	99,000	6,300	18,000
Lead	480	--	--	--	--	--	--	260	260
Manganese	200	--	340	--	78	2,000	200	180	300
Molybdenum	90	--	--	--	--	--	--	--	22
Nickel	540	190	350	310	--	370	470	210	150
Rubidium	52	--	--	--	--	--	--	--	74
Silver	--	--	--	--	--	--	--	--	--
Strontium	72	130	--	--	--	200	--	--	110
Thorium	--	--	--	--	--	--	--	--	--
Tin	--	--	--	--	--	--	--	--	--
Titanium	660	890	1,400	530	530	890	1,100	890	3,100
Tungsten	--	--	--	--	--	--	--	--	--
Uranium	--	--	--	--	--	--	--	--	--
Vanadium	--	--	90	--	--	--	--	--	--
Yttrium	84	--	--	--	--	--	--	--	27
Zinc	230	150	300	140	210	250	180	150	190
Zirconium	120	--	--	--	--	--	--	--	52

APPENDIX C

WATER DATA

Reproduced from best available copy.

TABLE C-1. WATER DATA
ENERGY FUELS MINE, COLORADO

Samples	Pond 1	Pond 2	Pond 3	Spoils Flume	Stream	Lysimeter SL-3	Lysimeter SL-4	Well S-6	Well S-9	Well S-10	Well D-6	Well CD-7	Well CD-8	Well D-9	Well D-14
Field Measurements															
Temperature (°C)	13.8	14	17	10.2	14.5	10	4	7.2	10.2	7.2	9.0	6.3	13.7	11.4	8.0
pH	9.2	8.1	6.2	8.4	8.0	7.7	6.5	7.4	7.2	7.6	7.9	10.0	7.7	9.6	6.5
Dissolved O_2 (mg/l)	14	21		16	10	3		14	11	8	14	13	9.1		
Conductivity (µmhos)	450	1,850	2,400	1,750	2,000	2,100	1,700	1,180	1,380	710	800	240	450	780	880
Salinity (°/oo)	0.8	1.8	2.3	1	1.8	2	2	0.5	0.7	0			0	0	1.2
Laboratory Determinations															
Organic															
Total Organic C (ppm)	20.5	3.5	10.9	2.4	14.7	81.2		5.6	6.4	5.9	6.0	4.4	3.0	115	4.8
Phenols (ppm)	<0.003	<0.001	<0.001	<0.001	0.003			0.012	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Tannin + Lignin (ppm)	0.84	<0.05	<0.05	<0.05	0.47			<0.02	<0.05	0.05	<0.005	0.08	<0.05	<0.09	0.09
Physical															
Total Alpha Activity (pCi/l)	6.0±2.7	11±6	24±8	8.7±5.1	19±7			6.4±1.2	6.8±3.9	3.1±1.3	2.0±2.3	2.7±1.1	2.8±1.6		17±5
Total Beta Activity (pCi/l)	0±16	8±19	0±21	0±8.5	5±22			17±10	0±13	0±8	10±6	28±10	0±7.2		38±19
Laboratory Determinations															
Inorganic (mg/l)															
HCO_3^{-1}	141	273	141	296	544	271	219	384	547	571	490	269	312	543	454
Br^{-1}	<0.02	0.25		0.65	<0.02			0.58	16		<0.1	0.26		<0.1	
CO_3^{-2}	53	2	0	0	0	0	0	0		0		5	0	48	0
Cl^{-1}	17	10	10	10	55	59	47	13	16	11	33	32	10	10	18
F^{-1}	1.0	2.1	0.9	0.5	3.2	1.1	0.9	0.7	0.6	0.9	0.46	0.7	0.5	0.2	4.7
$NO_2^{-1} + NO_3^{-1}$	0.2	2.7		1.0	0.5			0.4	0.8	0.3	5.1	0.3	0.7	0.4	<0.1
PO_4^{-3}				<0.1					2.1	<0.1	<0.1	<0.1	<0.1	<0.1	
SO_4^{-2}	68	1,450	1,750	1,440	1,540	1,650	1,450	735	800	176	263	1,393	70	100	500
SiO_2	4.2	6.3	<0.1	0.9	<0.1			9.6	1.9	7.5	11.5	13.3	1.6	85.8	9.6
Al	0.3	0.3	0.3	<1.0	0.3	0.5	0.5	<0.1	<1.0	0.3	<1.0	<0.1	<1.0	<2.0	1.2
As	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.003	<0.005	<0.003	<0.005	<0.005	<0.005	<0.005	<0.005
Ba				<0.2					<0.2		<1.0		<0.2	<1.0	
B	<0.1	<0.1	<0.1	<0.1	<0.1			<0.1	<0.1	<0.1	<0.5	<0.1	<0.1	<0.5	<0.1
Cd	<0.04	<0.03	<0.01	<0.1	<0.04	0.01	0.01	<0.03	<0.1	<0.03		<0.03	<0.1		<0.04
Ca	36	365	429	400	250	407	229	242	153	41	14	28	36	5.4	79
Cr	<0.05	<0.03	<0.05	<0.1	<0.05	<0.005	<0.005	<0.05	<0.1	<0.05	<0.1	<0.05	<0.1	<0.1	<0.05
Cu	<0.04	0.06	0.03	<0.1	<0.04	0.03	0.01	<0.04	<0.1	<0.04	<0.04	<0.04	<0.1	<0.04	<0.04
Fe	<0.1	0.3	0.4	0.1	0.1	0.50	0.10	0.2	0.5	0.4	<0.2	<0.1	0.1	1.3	0.7
Pb	<0.03	0.06	<0.01	<0.2	<0.03	0.02	0.09	0.05	<0.2	<0.03	<0.1	<0.03	<0.2	<0.1	0.03
Li				<0.1					0.1		0.1		0.1	<0.1	
Mg	37	127	151	187	229	176	122	105	106	20	8	15	19	1.2	24
Mn	<0.1	<0.1	<0.1	0.1	0.9	3.4	0.05	0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Hg	<0.0001	0.0001	0.009	0.0001	<0.0001			0.0003	0.0001	<0.0001		0.0001	0.0002		<0.0001
Mo	<0.01	0.02	<0.01	<0.02	0.10			<0.01	0.11	0.02	<0.01	<0.01	<0.02	0.03	0.02
Ni	<0.1	<0.1	<0.1	<0.1	<0.1	0.08	0.10	<0.1	<0.1	<0.01	<0.1	<0.1	<0.1	<0.1	<0.1
K	2.2	2.9	5.2	3.7	2.6	22	6	1.4	3.9	3.3	2.0	25	2.6	2.7	3.0
Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Na	33	30	30	38	134	200	371	59	223	200	286	18	108	271	237
Sr	0.3	3.1	4.3	3.5	1.8	5	2	1.4	2.0	0.7	0.6	0.35	1.6	0.1	1.5
Ti	2.09	0.56	0.65	0.53	1.46	0.0	<0.10	0.40	0.23	0.68	0.25	0.22	0.08	0.32	0.44
Zn	<0.1	<0.1	0.04	0.4	0.1	0.48	0.22	0.10	0.4	0.2	0.1	0.1	0.2	0.2	<0.1

TABLE C-2. WATER DATA
EDNA MINE, COLORADO

Samples	Pond 1	Pond 2	Pond 3	Spring 1	Spring 2	Spring 3	Spring 4	Lysimeter SL-3	Lysimeter SL-10	Lysimeter SL-12	Well S-5	Well S-7	Well S-8
Field Measurements													
Temperature (°C)	25	24	16.8	9.8	10.0	10.3	11.5	8.5	12	7	10	8	14
pH	8.2	8.3	7.3	7.2	7.1	7.6	7.4	6.8	6.9	8.4	7.0	7.3	7.1
Dissolved O_2 (mg/l)	9	14		15	17	15	15	4	2	2	3	5	8
Conductivity (µmhos)	2,380	2,170	2,180	1,625	1,640	1,810	2,000	1,940	2,400	4,050	1,220	140	560
Salinity (°/oo)	1	2.1	2.0	1.0	1.0	1.6	1.8	1.5	2	2.5	0.5	0	0
Laboratory Determinations													
Organic													
Total Organic C (ppm)	5.3	4.0	4.1	3.4	2.7	2.8	3.5	9.4	16.7	11.5	3.9	2.2	15.43
Phenols (ppm)	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001				<0.001	0.008	0.012
Tannin + Lignin (ppm)	<0.02	<0.02	0.05	<0.002	<0.002	<0.02	<0.02				<0.02		
Physical													
Total Alpha Activity (pCi/l)	6.4±4.9	3.1±3.8	11±5	4.5±2.1	4.5±3.5	8.7±5.5	0±3.5				12±4	3.0±1.4	0.4±1.2
Total Beta Activity (pCi/l)	13±22	4±21	26±19	0±16	0±23	0±22	11±22				20±12	0±9	12±10
Laboratory Determinations													
Inorganic (mg/l)													
HCO_3^{-1}	128	53	107	168	247	163	162	137	253	730	410	116	181
Br^{-1}	0.45	<0.02	0.07	0.30	0.36	0.34	0.49	<0.02		<0.02		0.41	
CO_3^{-2}	0	2	0	0	0	0	0	0	0	0	0	0	0
Cl^{-1}	13	14	13	10	10	10	12	11	47	22	14	4	14
F^{-1}	1.2	1.6	2.0	0.6	0.6	1.6	2.2	0.7	0.8	0.8	1.1	1.1	1.2
$NO_2^{-1} + NO_3^{-1}$	0.4	0.3	<0.1	1.0	0.4	0.4	0.4				0.7	0.4	2.2
PO_4^{-3}				<0.1	<0.1								
SO_4^{-2}	230	1,488	1,250	1,650	1,563	1,563	1,725	1,875	1,634	2,975	775	25	1,530
SiO_2	7.7	0.5	<0.1	0.7	3.7	10.5	10.1				5.8	11.2	5.8
Al	<0.1	0.1	0.1	<0.1	<0.1	0.1	0.1	0.5	0.5	0.5	<0.1	<0.1	<0.1
As	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.003	<0.005
Ba				<0.2	<0.2								
B	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				<0.1	<0.1	<0.1
Cd	<0.03	<0.03	<0.04	<0.1	<0.1	<0.03	<0.03	0.01	0.01	0.01	<0.03	<0.03	<0.03
Ca	500	386	415	407	415	472	486	440	420	170	276	26	276
Cr	0.14	<0.05	<0.05	<0.1	<0.1	<0.5	<0.05	<0.005	<0.005	<0.005	<0.05	<0.05	<0.05
Cu	<0.04	<0.04	<0.04	<0.1	<0.1	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Fe	0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	12	0.5	6.6	0.2	2.0
Pb	0.07	0.05	0.05	<0.1	<0.1	0.06	0.06	0.05	<0.01	0.20	0.05	<0.03	<0.03
Li				<0.1	<0.1								
Mg	150	113	151	169	150	178	157	182	111	158	92	10.7	29
Mn	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	7.5	0.2	0.1	0.2	0.8
Hg	0.0006	0.004	<0.0001	<0.0001	<0.0001	<0.0001	0.0001				<0.0001		0.0007
Mo	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01				<0.01	<0.01	<0.01
Ni	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.1	0.1	<0.1	<0.1	0.1
K	4.7	2.7	2.6	2.2	2.6	2.2	3.2	4.0	5.0	38	4.0	1.3	6.6
Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.008	<0.005	<0.005	<0.005
Na	26	25	22	11.4	13.7	14	25	26	86	1,140	24	4.8	14
Sr	1.9	2.6	2.4	1.6	1.7	2.0	2.6	1.5	2.2	13	3.3	0.1	0.4
Ti	0.34	0.34	0.59	0.05	0.03	0.20	0.23		0.72	0.72	0.30	0.20	0.43
Zn	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	2.3	0.1	0.1	0.1	0.2

TABLE C-3. WATER DATA
McKINLEY MINE, NEW MEXICO

Samples	Pit 32	Pit 33	Pit 34	Pit 37	Well 1	Well 2	Well 4	Well 5	Well 6	Well 7	Well 8	Well 11	Well 12	Well 13	Well 14
Field Measurements															
Temperature (°C)	8.5	9.5	10.0	4.0	10.5	8.5	12.5	13.0	11.0	12.5	12.5	11.0	9.5	7.5	12.0
pH	8.2	8.1	8.2	8.2	7.7	7.75	6.8	7.0	8.5	6.5	7.0	6.5	7.0	7.4	8.1
Dissolved O_2 (mg/l)	2	8	2	2	2	3	2	2	2	4	2	3	3	4	2
Conductivity (μmhos)	2,325	2,300	1,800	2,450	1,475	2,400	4,000	5,500	1,625	2,000	2,000	4,700	3,800	2,225	2,300
Salinity (°/oo)	2.0	2.0	2.0	2.5	1.5	2.5	3.5	4.75	1.5	2.0	2.0	4.0	4.0	2.0	2.0
Laboratory Determinations															
Organic															
Total Organic C (ppm)	20.3	29	25.6	21.3	7.1		201		14.0		141	30.7			26.1
Phenols (ppm)	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001		<0.001		<0.001	<0.001	<0.001		<0.001
Tannin + Lignin (ppm)	0.40	0.18	0.31		0.41	0.45	0.81		3.4		0.90	0.48	0.23		1.1
Physical															
Total Alpha Activity (pCi/l)	41±12	37±10	18±6	35±11	140±15	67±13	12±7		56±9		17±3	41±16	47±19		22±7
Total Beta Activity (pCi/l)	85±44	34±24	26±20	0±36	57±21	58±33	48±37		12±13		0±10	0±56	0±73		0±20
Laboratory Determinations															
Inorganic															
HCO_3^{-1}	660	590	390	610	1,170	854	1,380	760	1,560	480	1,180	910	910	810	810
Br^{-1}	<0.02	0.09	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
CO_3^{-2}	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0
Cl^{-1}	60	40	30	50	30	50	50	80	20	50	20	90	40	70	20
F^{-1}	2.3	1.1	1.2	1.6	3.3	2.8	2.3	0.6	3.1	0.5	2.2	1.9	2.3	1.3	5.8
$NO_2^{-1} + NO_3^{-1}$	16	5.0	2.2	100	1.4	4.4	40		25		6.7	70	11.0		2.3
PO_4^{-3}	0.36	0.027	0.027	0.047	0.04	<0.06	<0.01		0.094		0.12	0.41	0.25		0.01
SO_4^{-2}	1,740	1,450	1,180	1,840	271	1,187	1,930	2,800	107	1,310	509	2,940	2,940	1,350	967
SiO_2	7.60	7.60	1.9	9.5	22.8	22.8	13.3	22.8	95.7	33.9	20.8	11.3	20.8	11.3	11.3
Al	0.06	0.45	0.1	0.6	0.3	0.7	0.7		8.4	2.12	5.8	1.4	7.0		5.5
As	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
Ba	<0.05	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
B	<0.05	<0.5	<0.5	<0.5	4.0	2.9	7.9	5.9	19.1	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	<0.05	0.008	<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	0.016	<0.05	<0.05	<0.05		<0.05
Ca	121	156	87.9	121	12.0	18.8	38.2	273	14.9	284	49.8	157	105	92.2	11.4
Cr	<0.05	0.004	<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	0.01	<0.05	<0.05	0.05		<0.05
Cu	<0.05	0.038	0.07	0.05	<0.05	<0.05	<0.05		0.13	0.096	0.11	0.07	0.07		0.06
Fe	<0.1	0.069	<0.1	0.3	<0.01	0.3	0.4		9.5	0.332	7.1	1.0	6.5		3.7
Pb	0.04	0.105	0.04	0.07	0.02	0.04	0.05		0.03	0.162	0.03	0.07	0.08		0.05
Li	0.15		0.054	0.15	0.047	0.012	0.205	0.275	0.09	0.15	0.096	0.31	0.22	0.065	0.015
Mg	58.3	78.8	30.2	60.3	4.1	5.4	12.6	11.6	4.33	94.5	13.8	85.4	35.9	38.9	3.38
Mn	<0.05	0.012	0.20	<0.05	<0.05	<0.05	<0.05		0.23	0.485	0.27	0.30	0.19		0.09
Hg	<0.001	0.015	<0.001	<0.001	0	0	0	0	0	0	0	0	0.004	0	<0.001
Mo	0.20	0.14	0.20	0.20	0.34	0.26	0.22	0.40	0.28	0.51	0.16	0.13	0.14		0.24
Ni	<0.1	0.12	<0.1	<0.1	<0.1	<0.1	<0.1		<0.1	0.158	<0.1	<0.1	<0.1		<0.1
K	12.1	9.61	9.03	10.6	5.51	4.28	6.92	18.6	4.43	14.7	7.19	11.6	10.1	13.9	3.25
Se	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Na	729	540	453	757	472	742	1,320	1,390	553	273	532	1,390	1,490	680	596
Sr	3.82	2.96	1.12	3.54	0.50	1.02	2.04	5.14	0.66	4.10	1.74	6.86	6.64	3.16	0.68
Ti	0.33	0.223	0.28	0.31	0.20	0.32	0.19	0.65	0.10	0.70	0.12	0.37	0.22		0.11
Zn	<0.05	0.036	<0.05	<0.05	<0.05	<0.05	<0.05		0.25	0.772	0.17	0.05	0.08		0.06

TABLE C-4. WATER DATA
MEDICINE BOW MINE, WYOMING

Samples	Pit 1	Pit 2	Pit 2A (repeat)	Pit 3	Pit 4	Pit 5	Pit 66	S3-B	Lake (Seminoe Reservoir)	Water Truck	Well 33-4-1	Well 33-4-9 (repeat)	Well 33-11-1	Well 33-11-1
Field Measurements														
Temperature (°C)	10.5	6.5	15.0	7.0	14.5	9.5	14.0	6.5	15.0	5.0	10.0	11.0	14.0	13.5
pH	6.0	6.0	7.9	6.0	6.5	5.0	7.2	6.0	7.8	6.5	6.5	8.2	11.0	12.0
Eh (mv)			180				200		165			210		60
Dissolved O_2 (mg/l)	2	5	9	4	8	8	6	4	5	6	3	4	7	6
H_2S (mg/l)			0.1	0.1		0.1	0.1		0.1		0.1	0.1	0.1	0.1
Conductivity (µmhos)	3,625	4,125	6,000	3,950	2,500	2,375	6,000	6,000	425	1,675	2,400	3,900	3,950	5,537.5
Salinity (°/oo)	3.0	3.5		3.5	2.25	2.0	4.5	5.0		1.75	2.0		3.5	3.5
Laboratory Determinations														
Organic														
Total Organic C (ppm)	21.4	32.8	27.4	37.7	18.7	30.7	43.5	49.5	10.7	16.6	5.1	88.4	95.3	25.4
Phenols (ppm)	<0.001	<0.001	<0.001	<0.001	<0.001	0.014	<0.001	<0.001	0.007	<0.001		0.002		0.038
Tannin + Lignin (ppm)	0.10	0.67	0.16	0.42	0.24	0.28	1.0	1.4	0.27	0.15		0.09		0.48
Physical														
Total Alpha Activity (pCi/l)	50±16	54±18	68±18	91±23	39±10	45±9	120±30	47±25	17±4	32±9	30±10	19±11		22±10
Total Beta Activity (pCi/l)	43±56	0±60	0±42	0±56	7±54	25±23	20±70	0±100	6±17	0±29	10±23	0±45		15±41
Laboratory Determinations														
Inorganic (mg/l)														
HCO_3^{-1}	410	180	390	675	290	189	668	650	113	250	598	309	0	0
Br^{-1}	<0.02	<0.02	0	<0.02	0	0	0	0	0.15	<0.02	0	0	0	0
CO_3^{-2}	0	30	0	0	0	0	0	0	0	0	0	0	60	90
Cl^{-1}	46	61	100.0	66	35	27	137.4	70	22.0	40	37.2	52.5	30	33.7
F^{-1}	0.09	0.07	0.06	0.09	0.09	0.14	0.07	0.35	0.10	0.09	0.07	0.06	0.09	0.09
$NO_2^{-1} + NO_3^{-1}$	97.3	106	117.0	121	63.9	0.34	60.5	70.9	0.66	93.9	0.63	1.81	22.1	0.85
PO_4^{-3}	0.50	0.07	0.18	0.40	0.22	0.28	0.04	<0.01	0.21	0.25	0.05	0.30	0.05	0.11
SO_4^{-2}	3,190	3,950	3,516	3,880	1,760	1,070	5,118	8,360	70	1,560	1,905	2,350	1,430	760
SiO_2	5.4	6.1	2.1	9.6	0.8	0.36	9.4	7.6	10.6	1.7	15.4	69	9.3	0.5
Al	0.07	0.1	0.08	0.2	<0.05	0.05	0.2	0.10	0.08	<0.05	0.08	0.4	0.3	0.3
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ba	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
B	5.7	5.8	6.2	5.0	3.6	2.6	2.3	5.6	3.1	7.7	18.3	6.7	6.7	3.0
Cd	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ca	381	445	431	515	262	215	559	400	31.8	222	335	365	736	582
Cr	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cu	0.007	0.007	<0.05	0.008	<0.05	<0.05	0.07	0.07	<0.05	<0.05	0.05	0.05	0.11	0.08
Fe	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	0.7	<0.1	<0.1	<0.1
Pb	0.02	0.03	0.03	0.04	0.02	0.02	0.04	0.07	<0.005	0.03	0.02	0.02	0.02	0.05
Li	<0.3	<0.3	<0.1	<0.3	<0.3	<0.3	<0.3	<0.3	<0.1	<0.3	<0.3	<0.1	<0.3	0.3
Mg	390	484	450	497	193	193	621	808	10.2	174	252	257	<1	<0.2
Mn	0.19	0.15	0.07	0.21	0.24	0.30	0.75	1.06	<0.05	0.19	0.16	0.07	<0.05	<0.05
Hg	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		0.001		<0.001
Mo	<0.01	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.08	<0.01
Ni	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
K	10.7	13.2	14.2	11.2	10.0	8.3	15.8	13.7	2.0	8.6	7.2	13.8	45.0	110
Se	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Na	460	576	515	521	234	95	812	1,150	19.9	215	165	318	178	189
Sr	17.2	17.8	16.3	14.6	8.0	1.5	19.8	6.3	<0.5	7.0	11.9	11.5	16.7	34.3
Ti	0.27	0.34	0.26	0.57	0.17	0.17	0.50	0.50	0.06	0.55	0.02	0.24	0.06	0.03
Zn	<0.05	0.07	<0.05	0.08	<0.05	0.05	0.06	0.05	<0.05	0.15	0.05	<0.05	<0.05	0.31

Reproduced from best available copy.

TABLE C-5. WATER DATA
ROSEBUD MINE, WYOMING

Samples	Pond 1	Pond 3	Pond 4	R-1	R-2	Pit 4 (R4-P4)	Pit 4S	Well 1	Well 2	Well 3	Well 34R4-16-1	Nugget N-1	Nugget N-2	Nugget N-3	Nugget N-4	Well 3R4S-15-1
Field Measurements																
Temperature (°C)	18.5		14.0	12.0	11.0	12.0	14.0	11.4	10.0	9.0	11.0	15.0	13.0	15.0	12.0	3.0
pH	7.1		7.6	7.1	7.9	8.1	7.9	7.0	6.9	6.9	7.2	3.55	7.9	7.9	8.5	7.1
Eh (mv)	140		185	180	195	80	160	220	180	180	190	370	190	145	135	
Dissolved O_2 (mg/l)	7		6	5	7	4	21	28	2	2	4	6	5	5	205	3
H_2S (mg/l)	0.1		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	<0.1
Conductivity (μmhos)	1,200		800	2,650	1,525	4,950	2,275	3,565	2,000	1,600	2,300	4,525	5,750	6,000	16,500	1,700
Salinity (°/oo)	1.5		1.0	2.5	1.5	2.0	2.0	3.35	2.0	1.5	2.0	4.0	4.8	5.0	14.8	1.5
Laboratory Determinations																
Organic																
Total Organic C (ppm)	12.5	39.5	7.2	11.3	13.4	11.8	14.2	96.2	13.9	20.0	16.5	3.8	33.7	29.2	271	19
Phenols (ppm)	0.005	0.005	0.012	0.008	0.010	0.002	0.005	<0.001	0.002	<0.001	0.004	0.010	0.006	<0.001	0.001	<0.001
Tannin + Lignin (ppm)	0.34	0.52	0.41	0.25	0.34	0.06	0.24	0.89	0.15		0.26	10.9	0.14	0.17	<0.2	0.14
Physical																
Total Alpha Activity (pCi/l)	23±5	20±12	19±5	70±16	140±20	30±8	52±11		42±10	14±6	14±8					17±6
Total Beta Activity (pCi/l)	48±14	17±51	2±25	4±35	100±40	21±19	41±26		15±22	35±21	0±33					0±16
Laboratory Determinations																
Inorganic (mg/l)																
HCO_3^{-1}	194	455	0	236	244	342	506	805	549	622	543	0	351	339	623	516
Br^{-1}	0.08	0	0	0	0.37		0	0	0	0	0	0	0	0.65	0	<0.01
CO_3^{-2}	0	0	0	0	0		0	0	0	0	0	0	0	0	136	0
Cl^{-1}	23	64	17	23	25	23	33	65	29	19	19	38	73	95	555	9
F^{-1}	0.16	0.11	0.20	0.11	0.12	0.18	0.09	0.14	0.15	0.10	0.18	0.59	0.44	0.33	0.66	<0.05
$NO_2^{-1} + NO_3^{-1}$	0.96	11.7	12.8	2.32	1.96	12.5	31.5	23.6	42.7	1.51	0.81	3.09	18.0	0.99	41.2	0.7
PO_4^{-3}	0.12	0.06	0.16	0.15	0.08	0.11	0.05	0.19	0.10	0.13	0.16	0.13	0.97	0.19	0.73	42.6
SO_4^{-2}	588	3,306	472	2,584	1,173	1,921	1,529	3,465	1,546	1,059	2,043	4,495	4,885	5,844	18,854	803
SiO_2	1.7	1.4	2.4	0.3	1.0	3.3	8.1	21.4	16.3	12.6	18.8	24.4	4.1	1.0	0.35	19.5
Al	<0.05	0.2	<0.5	0.1	<0.5	0.05	<0.05	0.3	<0.05	<0.05	0.1	15.2	0.2	0.2	0.6	0.28
As	<0.01	<0.01	0.01	<0.01	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.02	<0.01
Ba	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
B	0.5	0.85	0.4	2.3	9.1	8.2	2.4	1.9	1.1	0.5	0.2	0.5	0.5	0.85	0.7	0.7
Cd	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	<0.5
Ca	119.5	403	124	277	145	349	354	609	345	208	481	468	522	481	411	258
Cr	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05
Cu	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	0.12	<0.05
Fe	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	0.1	<0.1	0.2	<0.1	9.3	<0.1	<0.1	0.2	1.8
Pb	0.01	0.05	0.009	0.03	0.02	0.02	0.03	0.04	0.03	0.06	0.03	0.05	0.04	0.08	0.26	0.02
Li	0.1	0.2	<0.2	<0.1	<0.1	0.2	<0.2	<0.2	<0.2	<0.2	0.1	0.4	0.6	0.5	0.2	0.062
Mg	73.5	447	45	342	157	163	176	550	231	113	283	751	970	1,170	4,870	126
Mn	<0.05	0.87	<0.05	0.06	0.06	0.23	0.14	2.39	0.22	0.27	0.48	9.42	0.41	0.37	0.44	0.08
Hg	<0.001			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		<0.001					0.02
Mo	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.05
Ni	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	<0.1	<0.1	0.3	<0.05
K	9.75	16.0	5.8	13.2	9.0	10.8	10.1	9.0	8.0	9.3	13.3	19.1	38.2	34.5	60	6.42
Se	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Na	70.5	373	31.2	60.0	95.0	111	183	163	89	235	73.0	73	128	202	1,100	90.2
Sr	2.45	13.0	1.0	3.22	2.30	8.8	10.8	11.2	7.6	9.1	10.3	4.2	6.0	6.2	5.4	11.0
Ti	0.16	0.30	0.14	0.04	0.06	0.13	0.05	0.11	0.06	0.10	<0.1	0.03	0.14	0.13	0	<0.01
Zn	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.22	<0.05	<0.05	0.05	1.24	<0.05	<0.05	<0.05	<0.05

TABLE C-6. WATER DATA
KEMMERER MINE, WYOMING

	Pit 1-V	Pit 1-G (repeat)
Field Measurements		
Temperature (°C)	19	14
pH	8.0	8.0
Dissolved O_2 (mg/l)	8	8
H_2S (mg/l)		
Conductivity (μmhos)	2,550	
Salinity (°/oo)		
Laboratory Determinations		
Organic		
Total Organic C (ppm)	7	4
Phenols (ppm)	<0.001	<0.001
Tannin + Lignin (ppm)	0.017	0.16
Physical		
Total Alpha Activity (pCi/l)	18±7	24±8
Total Beta Activity (pCi/l)	0±20	0±20
Laboratory Determinations		
Inorganic (mg/l)		
HCO_3^{-1}	146.7	147.5
Br^{-1}	0.01	<0.01
CO_3^{-2}	0.0	0.0
Cl^{-1}	19	20
F^{-1}	0.20	0.20
$NO_2^{-1} + NO_3^{-1}$	5.9	<0.1
SO_4^{-2}	2,025	2,025
SiO_2	0.70	0.70
Al	0.28	0.23
As	<0.01	<0.01
Ba	<0.5	<0.05
B	0.4	0.9
Cd	<0.05	<0.05
Ca	382	382
Cr	0.07	0.07
Cu	<0.05	<0.05
Fe	0.77	0.15
Pb	0.008	0.01
Li	0.223	0.225
Mg	344	344
Mn	0.39	0.06
Hg	<0.001	<0.001
Mo	0.06	<0.01
Ni	0.06	<0.05
K	20.1	20.1
Se	<0.01	<0.01
Na	44.8	45.4
Sr	5.55	5.55
Ti	0.01	<0.01
Zn	<0.05	<0.05

TABLE C-7. WATER DATA
WYODAK MINE, WYOMING

Samples	Pond 1	HW-1	Donkey Creek
Field Measurements			
Temperature (°C)	26	21	29
pH	7.8	7.4	8.2
Dissolved O_2 (mg/l)	5	3	7
H_2S	<0.1	<0.1	<0.1
Conductivity (μmhos)	2,725	2,825	3,900
Salinity (°/oo)	0	2.2	3.0
Laboratory Determinations			
Organic			
Total Organic C (ppm)	14	6	17
Phenols (ppm)	<0.001	<0.001	<0.001
Tannin + Lignin (ppm)	0.63	1.3	0.32
Physical			
Total Alpha Activity (pCi/l)	28±9	12±7	29±10
Total Beta Activity (pCi/l)	7±22	0±22	0±27
Laboratory Determinations			
Inorganic (mg/l)			
HCO_3^{-1}	545.1	563.7	492.9
Br^{-1}	<0.01	0.01	<0.01
CO_3^{-2}	0.0	0.0	0.0
Cl^{-1}	19	263	203
F^{-1}	0.50	0.76	1.63
$NO_2^{-1} + NO_3^{-1}$	2.2	0.9	0.7
SO_4^{-2}	1,390	1,701	1,714
SiO_2	11.3	14.5	18.0
Al	0.15	0.06	0.13
As	<0.01	<0.01	<0.01
Ba	<0.5	<0.5	<0.5
B	<0.1	<0.1	0.2
Cd	<0.05	<0.05	<0.05
Ca	295	425	250
Cr	0.05	0.06	0.07
Cu	<0.05	<0.05	<0.05
Fe	<0.10	0.42	<0.10
Pb	0.03	0.02	0.09
Li	0.091	0.111	0.199
Mg	164	249	294
Mn	0.07	1.0	0.35
Hg	<0.001	<0.001	<0.001
Mo	0.09	0.06	0.09
Ni	0.05	<0.05	<0.05
K	25.0	17.9	20.1
Se	<0.01	<0.01	<0.01
Na	276	338	366
Sr	4.51	5.21	4.02
Ti	0.06	0.01	0.06
Zn	<0.05	<0.05	<0.05

TABLE C-8. WATER DATA
COLSTRIP MINE, MONTANA

	Pit D-1	Pit D-2	Swimming Hole	Spring
Field Measurements				
Temperature (°C)	22	24	25	21
pH	7.8	8.0	7.9	7.7
Dissolved O_2 (mg/l)	9		6	9
H_2S (mg/l)	<0.1		<0.1	<0.1
Conductivity (μmhos)	1,150		4,450	
Salinity (o/oo)	0.9	4.5	3.0	0.8
Laboratory Determinations				
Organic				
Total Organic C (ppm)	4	15	9	7
Phenols (ppm)	0.018	0.026	0.018	0.008
Tannin + Lignin (ppm)	0.14	0.36	0.10	0.25
Physical				
Total Alpha Activity (pCi/l)	7.3±9	40±22	93±22	12±4
Total Beta Activity (pCi/l)	0±46	0±93	0±48	14±15
Laboratory Determinations				
Inorganic (mg/l)				
HCO_3^{-1}	250.1	549.1	175.1	401.0
Br^{-1}	<0.01	<0.01	<0.01	<0.01
CO_3^{-2}	0.0	0.0	0.0	0.0
Cl^{-1}	9	22	18	5
F^{-1}	<0.05	0.05	<0.05	0.76
$NO_2^{-1} + NO_3^{-1}$	1.1	0.2	0.5	4.9
SO_4^{-2}	3,015	5,043	3,769	397
SiO_2	1.0	5.0	0.8	24.5
Al	0.04	0.10	0.11	0.08
As	<0.01	0.01	<0.01	0.01
Ba	<0.5	<0.5	<0.5	0.5
B	0.6	1.6	0.4	<0.1
Cd	<0.05	<0.5	<0.05	<0.05
Ca	283	265	319	119
Cr	0.07	0.10	0.08	<0.05
Cu	<0.05	<0.05	<0.05	<0.05
Fe	<0.10	<0.10	<0.10	<0.10
Pb				
Li	<0.1		<0.1	<0.1
Mg	578	864	696	92.5
Mn	<0.05	<0.05	0.05	<0.05
Hg	<0.001	<0.001	<0.001	<0.001
Mo	0.04	0.04	0.02	0.06
Ni	0.06	0.08	0.07	<0.05
K	18.4	45.9	18.2	8.12
Se	<0.01	<0.01	<0.01	<0.01
Na	11.4	219	151	21.1
Sr	6.50	5.51	5.25	2.01
Ti	0.04	0.06	0.01	0.06
Zn	<0.05	<0.05	<0.05	<0.05

TABLE C-9. U.S.G.S. WATER RESOURCES DATA FOR COLORADO*
1975
GREEN RIVER BASIN
YAMPA RIVER BELOW CRAIG, COLORADO

	June 26	July 25	August 27	September 30
Temperature (°C)	11.5	18.0	16.0	13.0
pH	7.9	7.6	7.9	8.8
Total Dissolved Solids (mg/l)	82	104	183	259
Dissolved O_2 (mg/l)	ND	10.6	8.2	9.2
Ca (mg/l)	13	19	30	38
Mg (mg/l)	3.2	6.4	11	15
Na (mg/l)	11	8.7	18	28
K (mg/l)	2.6	1.0	1.8	4.1
Fe (μg/l)	100	100	50	40
SO_4 (mg/l)	11	22	48	76
HCO_3 (mg/l)	46	74	130	131
CO_3 (mg/l)	0	0	0	16
Cl (mg/l)	11	2.8	5.6	12

* This analysis is plotted on the Energy Fuels Mine vector diagram appearing in Sections 7 and 8.

TABLE C-10. U.S.G.S. WATER RESOURCES DATA FOR WYOMING*
1975
GROUND WATER IN CARBON COUNTY, WYOMING AND SURFACE WATER FROM HANNA DRAW, WYOMING

	O	N	K	April 28	May 16
	Carbon County Ground Waters			Hanna Draw	Hanna Draw
Temperature (°C)	10.0	10.0	7.0	13.0	23.5
pH	6.7	8.9	7.2	8.2	8.2
Total Dissolved Solids (mg/l)	5,350	2,240	3,970	2,190	2,590
Dissolved O_2 (mg/l)	ND**	ND**	ND**	9.4	9.0
Ca (mg/l)	510	270	240	250	290
Mg (mg/l)	420	200	250	170	180
Na (mg/l)	520	160	660	210	250
K (mg/l)	9.1	6.7	17	8.6	8.8
Fe (μg/l)	ND**	ND**	ND**	20	110
SO_4 (mg/l)	3,600	1,300	2,300	1,300	1,600
HCO_3 (mg/l)	487	548	975	472	483
CO_3 (mg/l)	0.0	0.0	0.0	0.0	0.0
Cl (mg/l)	29	11	16	15	19

* These analyses appear in the vector diagrams of water chemistries from the Medicine Bow Mine in Sections 7 and 8.

** Not Determined.

TABLE C-11. GROUND WATERS NEAR COLSTRIP MINE, WYOMING*

(from Van Voast and Hedges, 1976)

	1	2	3	4	5	6
	Aquifer Type					
	McKay Coal	Alluvium	Alluvium	Rosebud Coal	Rosebud Coal	McKay Coal
Temperature (°C)	ND**	7.0	8.5	13.0	10.0	ND**
pH	7.6	7.3	7.4	7.2	7.4	7.4
Total Dissolved Solids (mg/l)	2,980	2,990	2,900	1,880	1,410	1,740
Ca (mg/l)	349	253	229	243	123	112
Mg (mg/l)	309	304	300	202	160	65
Na (mg/l)	116	251	255	76	98	387
K (mg/l)	22	11	13	7.4	8.3	10
Fe (mg/l)	0.0	0.03	0.01	0.02	0.06	0.00
SO_4 (mg/l)	1,960	1,850	1,760	1,040	727	789
HCO_3 (mg/l)	402	571	614	601	518	714
CO_3 (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0
Cl (mg/l)	12	19	17	5.7	20	9.1

* These waters appear in a vector diagram for waters from the Colstrip Mine in Sections 7 and 8.

** ND = Not Determined.

TABLE C-12. GROUND WATERS IN WESTERN WYOMING*
(from Lines, G. C., and Glass, W. R., 1975;
Water resources of the thrust belt of
western Wyoming. U.S.G.S.
Map HA-539)

						Evanston		
	Cokeville (Alluvium)	Kemmerer (Hams Fork Fm.)	Jackson (Alluvium)	Thayne (Salt Lake Fm.)	Afton (Madison Limestone)	Evanston (Alluvium)	(Bear River Fm.)	(Wasatch Fm.)
Temperature (°C)	7.0	ND**	7.0	8.0	4.0	10.0	22.0	11.0
pH	7.5	7.9	7.8	8.0	8.2	8.3	7.5	7.6
Total Dissolved Solids (mg/l)	378	262	264	222	100	360	126	242
Ca (mg/l)	91	56	53	53	29	73	33	30
Mg (mg/l)	21	19	22	18	5.0	23	77	26
Na (mg/l)	7.6	6.5	2.2	1.0	0.0	30	2.0	24
K (mg/l)	1.4	ND**	1.8	0.7	0.7	1.7	0.8	5.3
Fe (µg/l)	20	ND**	420	40	60	ND**	ND**	440
SO_4 (mg/l)	130	101	83	30	9.9	26	4.5	12
HCO_3 (mg/l)	213	149	171	207	101	352	141	251
CO_3 (mg/l)	0.0	0.0	0.0	0.0	0.0	5	0.0	0.0
Cl (mg/l)	4.3	3.5	1.7	2.1	1.0	9.7	1.4	11

* These analyses are plotted on vector diagrams for waters from the Kemmerer Mine appearing in Sections 7 and 8.

** ND = Not Determined.

APPENDIX D

GEOCHEMICAL CALCULATIONS

TABLE D-1. GEOCHEMICAL CALCULATIONS POND 1 ENERGY FUELS MINE, COLORADO

Temperature, °C:	13.8
pH:	9.2
μ:	0.00768*
Surface:	Upstream

Input to WATEQ
(ppm)

Cations		Anions	
Ca	36	Cl	17
Mg	37	SO_4	68
Na	33	HCO_3	141
K	2.2	F	1.0
Sr	0.3		
Al	0.3	SiO_2	4.2

Mineral	Change in Free Energy of Reaction
Calcite	1.47442**
Dolomite	3.19277
Quartz	-0.02361

* Tables are ordered, mine by mine, on the basis of increasing ionic strength.

** Kcal Per Equiv.

TABLE D-2. GEOCHEMICAL CALCULATIONS
HOLE CD-8
ENERGY FUELS MINE, COLORADO

Temperature, °C:	13.7
pH:	7.68
μ:	0.0094946
Aquifer:	Sandstone

Input to WATEQ
(ppm)

Cations		Anions	
Ca	36	Cl	1.0
Mg	19	SO_4	70
Na	108	HCO_3	312
K	2.6	F	1.5
Fe	0.1		
Sr	1.6	SiO_2	1.6

Mineral	Change in Free Energy of Reaction
Calcite	0.08320*
Dolomite	0.01515
$Fe(OH)_3$	3.31946
Goethite	8.14056
Hematite	23.55368
Quartz	-0.51210

* Kcal Per Equiv, see Plummer, Jones, and Truesdell (36).

TABLE D-3. GEOCHEMICAL CALCULATIONS
U. S. GEOLOGICAL SURVEY WATER 50/630
GROUND WATER DRILLED TO MESA VERDE FORMATION DOWNSTREAM OF MINE
ENERGY FUELS MINE, COLORADO

Temperature, °C:	11.0
pH:	7.3
μ:	0.010399
Aquifer:	Sandstone

Input to WATEQ
(ppm)

Cations		Anions	
Ca	66	Cl	8.3
Mg	30	SO_4	63
Na	21	HCO_3	292
K	1.8	F	0.3
Mn	30		
		SiO_2	9.3

Mineral	Change in Free Energy of Reaction
Quartz	0.54639*
Birnessite	13.27196
Manganite	8.72381
Rhodochrosite	1.80908
Chalcedony	-0.15568
Dolomite	-0.62693

* Kcal Per Equiv.

TABLE D-4. GEOCHEMICAL CALCULATIONS
HOLE S-10
ENERGY FUELS MINE, COLORADO

Temperature, °C:	9.2
pH:	7.6
μ:	0.01569
Aquifer:	Alluvium Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	41	Cl	11
Mg	20	SO_4	176
Na	200	HCO_3	571
K	3.3	F	0.9
Fe	0.4		
Sr	0.7	SiO_2	7.5
Al	0.3		
Mn	0.1		

Mineral	Change in Free Energy of Reaction
Calcite	0.208*
Dolomite	0.127
$Fe(OH)_3$	3.904
Gibbsite	1.255
Goethite	8.422
Hematite	23.973
Quartz	0.462

* Kcal Per Equiv.

TABLE D-5. GEOCHEMICAL CALCULATIONS
HOLE D-6
ENERGY FUELS MINE, COLORADO

Temperature, °C:	9.0
pH:	7.9
μ:	0.017053
Aquifer:	Sandstone at Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	140	Cl	33
Mg	8.0	SO_4	265
Na	286	HCO_3	494
K	2.0	F	0.46
Sr	0.6		
		SiO_2	11.5

Mineral	Change in Free Energy of Reaction
Quartz	0.70504*
Calcite	-0.12997
Chalcedony	-0.00338
Dolomite	-0.45793
Silica Gel	-0.66605

* Kcal Per Equiv.

TABLE D-6. GEOCHEMICAL CALCULATIONS U.S. GEOLOGICAL SURVEY GROUND WATER DRILLED TO ALLUVIUM AT MESA VERDE FORMATION-LEWIS FORMATION CONTACT ON FOIDEL CREEK, COLORADO

Temperature, °C: 11.0
pH: 7.2
μ: 0.017922
Aquifer: Alluvium Downstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	47	Cl	12
Mg	17	SO_4	250
Na	210	HCO_3	443
K	2.5	F	0.3
Fe	10		
Mn	60	SiO_2	11.0

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	5.81667*
Hematite	28.09887
Quartz	0.64284
Birnessite	13.29877
Manganite	8.75056
Rhodochrosite	2.18450
Goethite	10.45620
Chalcedony	-0.05923
Calcite	-0.38567

* Kcal Per Equiv.

TABLE D-7. GEOCHEMICAL CALCULATIONS
HOLE D-14
ENERGY FUELS MINE, COLORADO

Temperature, °C:	8.0
pH:	6.5
μ:	0.022881
Aquifer:	Shale Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	79	Cl	18
Mg	24	SO_4	500
Na	237	HCO_3	454
K	3.0	F	4.7
Fe	0.7		
Si	1.5	SiO_2	9.6
Mn	1.2		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	3.92615*
Goethite	8.36391
Hematite	23.81861
Quartz	0.62709
Chalcedony	-0.085
Gibbsite	-0.21

* Kcal Per Equiv.

TABLE D-8. GEOCHEMICAL CALCULATIONS
HOLE S-6
ENERGY FUELS MINE, COLORADO

Temperature, °C:	7.2
pH:	7.4
μ:	0.031864
Aquifer:	Shale at Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	242	Cl	13
Mg	105	SO_4	735
Na	59	HCO_3	384
K	1.4	F	0.7
Fe	0.2		
Mn	0.1	SiO_2	9.6
Sr	1.4		

Mineral	Change in Free Energy of Reaction
Calcite	0.4988*
Dolomite	0.61415
$Fe(OH)_3$	3.4333
Goethite	7.8172
Hematite	22.6995
Quartz	0.6435
Birnessite	10.6408
Manganite	5.65912
Chalcedony	-0.0706
Silica Gel	-0.7302

* Kcal Per Equiv.

TABLE D-9. GEOCHEMICAL CALCULATIONS
HOLE S-9
ENERGY FUELS MINE, COLORADO

Temperature, °C:	10.2
pH:	7.22
μ:	0.034761
Aquifer:	Shale Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	153	Cl	16
Mg	106	SO_4	800
Na	223	HCO_3	547
K	3.9	F	0.6
Fe	0.5		
Sr	2.0	SiO_2	1.9
Mn	0.1		

Mineral	Change in Free Energy of Reaction
Calcite	0.24*
Dolomite	0.422
$Fe(OH)_3$	4.083
Goethite	8.67
Hematite	24.499
Birnessite	9.73
Manganite	5.09
Gypsum	-0.695
Quartz	-0.328

* Kcal Per Equiv.

TABLE D-10. GEOCHEMICAL CALCULATIONS
POND 2
ENERGY FUELS MINE, COLORADO

Temperature, °C:	14.0
pH:	8.1
μ:	0.044060
Surface:	At Mine in Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	365	Cl	10
Mg	127	SO_4	1,450
Na	30	HCO_3	273
K	2.9	F	2.1
Fe	0.3		
Sr	3.1	SiO_2	6.3
Al	0.3		

Minerals	Change in Free Energy of Reaction
Calcite	1.43333
Dolomite	2.51319
$Fe(OH)_3$	3.78966
Gibbsite	0.25767
Goethite	8.63112
Hematite	24.54456
Quartz	0.26485
Gypsum	-0.05182
Chalcedony	-0.42769

* Kcal Per Equiv.

TABLE D-11. GEOCHEMICAL CALCULATIONS
SPOILS FLUME
ENERGY FUELS MINE, COLORADO

Temperature, °C:	10.2
pH:	8.4
μ:	0.04863
Surface:	At Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	400	Cl	10
Mg	187	SO_4	1,440
Na	38	HCO_3	296
K	3.7	F	0.5
Fe	0.1		
Sr	3.5	SiO_2	0.9
Mn	0.1		

Mineral	Change in Free Energy of Reaction
Calcite	1.80231*
Dolomite	3.34282
Goethite	7.3789
Hematite	21.91883
Birnessite	12.47082
Manganite	7.7750
$Fe(OH)_3$	2.79309
Gypsum	-0.03162

* Kcal Per Equiv.

TABLE D-12. GEOCHEMICAL CALCULATIONS
HOLE SL-4
ENERGY FUELS MINE, COLORADO

Temperature, °C:	4.0
pH:	6.5
μ:	0.0488
Lysimeter:	In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	229	Cl	47
Mg	122	SO_4	1,450
Na	371	HCO_3	219
K	6.0	F	0.9
Fe	0.1		
Sr	2.0		
Al	0.5		
Mn	0.05		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	2.6428*
Gibbsite	1.5357
Goethite	6.8116
Hematite	20.5863
Birnessite	7.8472
Manganite	2.7525
Gypsum	-0.2606

* Kcal Per Equiv.

TABLE D-13. GEOCHEMICAL CALCULATIONS
STREAM 1
ENERGY FUELS MINE, COLORADO

Temperature, °C:	14.5
pH:	8.0
μ:	0.05235
Surface:	Downstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	250	Cl	55
Mg	229	SO_4	1,540
Na	134	HCO_3	544
K	2.6	F	3.2
Fe	0.1		
Sr	1.8		
Al	0.3		
Mn	0.9		

Mineral	Change in Free Energy of Reaction
Calcite	1.45944*
Dolomite	3.12559
$Fe(OH)_3$	3.23166
Gibbsite	0.34596
Goethite	8.10688
Hematite	23.51215
Birnessite	12.42877
Rhodochrosite	0.76268
Gypsum	-0.28906

* Kcal Per Equiv.

TABLE D-14. GEOCHEMICAL CALCULATIONS
HOLE SL-3
ENERGY FUELS MINE, COLORADO

Temperature, °C: 10.0
pH: 7.7
μ: 0.0558
Lysimeter: In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	407	Cl	59
Mg	176	SO_4	1,650
Na	200	HCO_3	271
K	22	F	1.1
Fe	0.5		
Sr	5.0		
Al	0.5		
Mn	3.4		

Mineral	Change in Free Energy of Reaction
Calcite	0.8587*
Dolomite	1.40826
$Fe(OH)_3$	4.03724
Gibbsite	1.30037
Goethite	8.6097
Gypsum	0.01702
Hematite	24.37414
Birnessite	12.56865
Manganite	8.08797
Rhodochrosite	0.68277

* Kcal Per Equiv.

TABLE D-15. GEOCHEMICAL CALCULATIONS
HOLE S-7
EDNA MINE, COLORADO

Temperature, °C:	8.0
pH:	7.3
μ:	0.00373844
Aquifer:	Alluvium Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	26	Cl	4.0
Mg	10.7	SO_4	25
Na	4.8	HCO_3	116
K	1.3	F	1.1
Fe	0.2		
Sr	0.1	SiO_2	11.2
Mn	0.2		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	3.48070*
Goethite	7.91820
Hematite	22.92690
Birnessite	10.7092
Manganite	5.9527
Chalcedony	-0.00246
Quartz	0.70914

* Kcal Per Equiv.

TABLE D-16. GEOCHEMICAL CALCULATIONS
HOLE S-5
EDNA MINE, COLORADO

Temperature, °C:	10.0
pH:	7.0
μ:	0.0322103
Aquifer:	Shale at Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	276	Cl	14
Mg	92	SO_4	775
Na	24	HCO_3	410
K	4	F	1.1
Fe	6.6		
Sr	3.3	SiO_2	5.8
Mn	0.7		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	5.49031*
Goethite	10.06259
Hematite	27.27975
Birnessite	9.95079
Manganite	5.47019
Calcite	0.14126
Quartz	0.30476
Chalcedony	-0.40049
Dolomite	-0.18598
Rhodochrosite	-0.75555
Gypsum	-0.38565

* Kcal Per Equiv.

TABLE D-17. GEOCHEMICAL CALCULATIONS
POND 1
EDNA MINE, COLORADO

Temperature, °C:	25.0
pH:	8.2
μ:	0.039036
Surface:	At Mine on Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	500	Cl	13
Mg	150	SO_4	230
Na	26	HCO_3	128
K	4.7	F	1.2
Fe	0.1		
Sr	1.9	SiO_2	7.70
Mn	0.1		

Mineral	Change in Free Energy of Reaction
Calcite	1.71168*
Dolomite	3.11818
$Fe(OH)_3$	3.59681
Goethite	9.17833
Hematite	25.9906
Quartz	0.14645
Birnessite	10.60774
Manganite	7.49941

* Kcal Per Equiv.

TABLE D-18. GEOCHEMICAL CALCULATIONS
POND 2
EDNA MINE, COLORADO

Temperature, °C:	24.0
pH:	8.3
μ:	0.041860
Surface:	At Mine on Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	386	Cl	14
Mg	113	SO_4	1,488
Na	25	HCO_3	53
K	2.7	F	1.6
Sr	2.6		
Al	0.1	SiO_2	0.5

Mineral	Change in Free Energy of Reaction
Calcite	0.97370*
Dolomite	1.64044
Gypsum	0.03634

* Kcal Per Equiv.

TABLE D-19. GEOCHEMICAL CALCULATIONS
SPRING 2
EDNA MINE, COLORADO

Temperature, °C:	10.0
pH:	7.05
μ:	0.047870
Surface:	In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	415	Cl	10
Mg	150	SO_4	1,563
Na	13.7	HCO_3	247
K	2.6	F	0.6
Sr	1.7		
		SiO_2	3.7

Mineral	Change in Free Energy of Reaction
Gypsum	0.04187*
Calcite	0.01220
Quartz	0.05437
Chalcedony	-0.65088
Dolomite	-0.38617

* Kcal Per Equiv.

TABLE D-20. GEOCHEMICAL CALCULATIONS
SPRING 1
EDNA MINE, COLORADO

Temperature, °C:	9.8
pH:	7.150
μ:	0.048996
Surface:	In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	407	Cl	10
Mg	169	SO_4	1,650
Na	11.4	HCO_3	168
K	2.2	F	0.6
Sr	1.6		
		SiO_2	0.7

Mineral	Change in Free Energy of Reaction
Gypsum	0.04823*
Calcite	-0.10051
Dolomite	-0.53594
Quartz	-0.87747

* Kcal Per Equiv.

TABLE D-21. GEOCHEMICAL CALCULATIONS
HOLE SL-10
EDNA MINE, COLORADO

Temperature, °C:	12.0
pH:	6.9
μ:	0.049507
Aquifer:	Shale Beneath Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	420	Cl	4.7
Mg	111	SO_4	1,634
Na	86	HCO_3	253
K	5.0	F	0.8
Sr	2.2		
Al	0.5		
Mn	7.5		
Fe	12		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	5.90274*
Gibbsite	2.07171
Goethite	10.60970
Hematite	28.43793
Birnessite	10.63247
Manganite	6.41393
Gypsum	0.06273
Rhodochrosite	0.13783
Calcite	-0.14390
Dolomite	-0.83358

* Kcal Per Equiv.

TABLE D-22. GEOCHEMICAL CALCULATION
SPRING 3
EDNA MINE, COLORADO

Temperature, °C: 10.3
pH: 7.6
μ: 0.050378
Surface: In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	472	Cl	10
Mg	178	SO_4	1,563
Na	14	HCO_3	163
K	2.20	F	1.6
Sr	2.0		
Al	0.1	SiO_2	10.5

Mineral	Change in Free Energy of Reaction
Kaolinite	6.47640*
Gibbsite	0.50916
Calcite	0.56123
Dolomite	0.74257
Gypsum	0.08625
Quartz	0.63460
Chalcedony	-0.06969

* Kcal Per Equiv.

TABLE D-23. GEOCHEMICAL CALCULATIONS
SPRING 4
EDNA MINE, COLORADO

Temperature, °C:	11.5
pH:	7.4
μ:	0.0518082
Surface:	In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	486	Cl	12
Mg	157	SO_4	1,725
Na	25	HCO_3	162
K	3.2	F	2.2
Sr	2.6		
Al	0.1	SiO_2	10.1

Mineral	Change in Free Energy of Reaction
Kaolinite	6.71891*
Calcite	0.31967
Dolomite	0.19818
Gibbsite	0.66577
Gypsum	0.14001
Quartz	0.58978

* Kcal Per Equiv.

TABLE D-24. GEOCHEMICAL CALCULATIONS
HOLE SL-3
EDNA MINE, COLORADO

Temperature, °C:	8.5
pH:	6.8
μ:	0.053743
Aquifer:	Shale Beneath Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	440	Cl	11.0
Mg	182	SO_4	1,875
Na	26.0	HCO_3	137
K	4.0	F	0.7
Sr	1.50		
Al	0.5		
Mn	0.3		

Mineral	Change in Free Energy of Reaction
Gibbsite	2.21566*
Gypsum	0.12664
Birnessite	9.14928
Manganite	4.47488

* Kcal Per Equiv.

TABLE D-25. GEOCHEMICAL CALCULATIONS
HOLE SL-12
EDNA MINE, COLORADO

Temperature, °C:	7.0
pH:	8.4
μ:	0.09416
Aquifer:	Shale Beneath Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	170	Cl	22
Mg	158	SO_4	2,975
Na	1,140	HCO_3	730
K	38	F	0.8
Fe	0.5		
Sr	13		
Al	5.0		
Mn	0.2		

Mineral	Change in Free Energy of Reaction
Calcite	1.54887*
Dolomite	3.15422
$Fe(OH)_3$	3.52036
Gibbsite	1.82927
Goethite	7.89147
Hematite	22.84242
Birnessite	12.76814
Manganite	8.03664
Rhodochrosite	0.22950
Gypsum	-0.3156

* Kcal Per Equiv.

TABLE D-26. GEOCHEMICAL CALCULATIONS
HOLE 1
McKINLEY MINE, NEW MEXICO

Temperature, °C:	10.5
pH:	7.7
μ:	0.026375
Aquifer:	Sandstone Upgradient of Pit 5

Input of WATEQ
(ppm)

Cations		Anions	
Ca	12	Cl	30
Mg	4.1	SO_4	271
Na	472	HCO_3	1,170
K	5.51	PO_4	0.04
Sr	0.5	F	3.3
Al	0.3		
B	4	SiO_2	22.8

Mineral	Change in Free Energy of Reaction
Chalcedony	0.36067*
Fluorapatite	4.72532
Gibbsite	1.01521
Kaolinite	8.35121
Quartz	1.06433
Calcite	-0.03607
Dolomite	-0.53817
Silica Gel	-0.30460

* Kcal Per Equiv.

TABLE D-27. GEOCHEMICAL CALCULATIONS
HOLE 6
McKINLEY MINE, NEW MEXICO

Temperature, °C:	11.0
pH:	8.5
μ:	0.028351
Aquifer:	Sandstone Upgradient of Pit 33

Input to WATEQ
(ppm)

Cations		Anions	
Ca	14.1	Cl	20
Mg	4.33	SO_4	107.0
Na	553	HCO_3	1,560
K	4.43	PO_4	0.094
Fe	9.5	F	3.1
Sr	0.66		
Al	8.4	SiO_2	95.7
B	19		
Mn	0.23		

Mineral	Change in Free Energy of Reaction
Calcite	1.23621*
Chalcedony	1.15425
Dolomite	1.93175
$Fe(OH)_3$	5.35136
Gibbsite	1.85249
Goethite	9.99119
Kaolinite	11.61863
Quartz	1.85632
Silica Gel	0.48812
Birnessite	12.81544
Manganite	8.49428
Rhodochrosite	1.14369

* Kcal Per Equiv.

TABLE D-28. GEOCHEMICAL CALCULATIONS
HOLE 14
McKINLEY MINE, NEW MEXICO

Temperature, °C: 12
pH: 8.1
μ: 0.039424
Aquifer:

Input to WATEQ
(ppm)

Cations		Anions	
Ca	11.4	Cl	20
Mg	3.38	SO_4	967
Na	596	HCO_3	810
K	3.25	PO_4	0.01
Fe	3.7	F	5.8
Sr	0.68		
Al	5.5	SiO_2	11.3
Mn	0.09		

Mineral	Change in Free Energy of Reaction
Calcite	0.08388*
$Fe(OH)_3$	5.12237
Gibbsite	2.03952
Goethite	9.82945
Kaolinite	9.57083
Quartz	0.63748
Birnessite	11.20402
Manganite	6.98541
Chalcedony	-0.06091
Dolomite	-0.32406
Rhodochrosite	-0.18397

* Kcal Per Equiv.

TABLE D-29. GEOCHEMICAL CALCULATIONS
PIT 34
McKINLEY MINE, NEW MEXICO

Temperature, °C:	10
pH:	8.2
μ:	0.039709
Surface:	Pit 5 Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	87.9	Cl	30.1
Mg	30.2	SO_4	1,180
Na	453	HCO_3	390
K	9.03	PO_4	0.027
Sr	1.12	F	1.20
Al	0.1		
Mn	0.2	SiO_2	1.9

Mineral	Change in Free Energy of Reaction
Calcite	0.90498*
Dolomite	1.36927
Kaolinite	3.07250
Birnessite	12.18373
Manganite	7.7601
Gibbsite	-0.22885
Quartz	-0.32700
Rhodochrosite	-0.00131

* Kcal Per Equiv.

TABLE D-30. GEOCHEMICAL CALCULATIONS
HOLE 7
McKINLEY MINE, NEW MEXICO

Temperature, °C:	12.5
pH:	6.5
μ:	0.046571
Lysimeter:	Pit 33 Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	282	Cl	50.0
Mg	94.5	SO_4	1,310
Na	273	HCO_3	480
K	14.7	F	0.5
Fe	0.38		
Sr	4.1	SiO_2	33.9
Al	0.35		
Mn	0.47		

Mineral	Change in Free Energy of Reaction
Chalcedony	0.56053*
$Fe(OH)_3$	3.77864
Gibbsite	1.85319
Goethite	8.51935
Kaolinite	10.44573
Quartz	1.25783
Birnessite	8.13425
Manganite	3.86855
Calcite	-0.47917
Gypsum	-0.22039
Silica Gel	-0.10820

* Kcal Per Equiv.

TABLE D-31. GEOCHEMICAL CALCULATIONS
HOLE 2
McKINLEY MINE, NEW MEXICO

Temperature, °C:	8.5
pH:	7.75
μ:	0.04754
Aquifer:	Sandstone Upgradient of Pit 5

Input to WATEQ
(ppm)

Cations		Anions	
Ca	18.8	Cl	50
Mg	5.4	SO_4	1,187
Na	74.2	HCO_3	854
K	4.28	F	2.8
Sr	1.02		
Al	0.7	SiO_2	22.8
B	2.9		

Mineral	Change in Free Energy of Reaction
Chalcedony	0.39409*
$Fe(OH)_3$	3.66868
Gibbsite	1.52136
Goethite	8.14036
Hematite	23.38774
Kaolinite	9.41167
Quartz	1.10410
Calcite	-0.14888
Silica Gel	-0.26772

* Kcal Per Equiv.

TABLE D-32. GEOCHEMICAL CALCULATIONS
PIT 33
McKINLEY MINE, NEW MEXICO

Temperature, °C:	9.5
pH:	8.1
μ:	0.0514477
Surface:	Highwall Pit 33

Input to WATEQ
(ppm)

Cations		Anions	
Ca	156	Cl	40
Mg	7.88	SO_4	1,450
Na	540	HCO_3	590
K	9.61	PO_4	0.027
Sr	2.96	F	1.10
		SiO_2	7.6

Mineral	Change in Free Energy of Reaction
Calcite	1.26501*
Dolomite	2.29449
Quartz	0.46655
Chalcedony	-0.24029
Gypsum	-0.49963

* Kcal Per Equiv.

TABLE D-33. GEOCHEMICAL CALCULATIONS
HOLE 13
McKINLEY MINE, NEW MEXICO

Temperature, °C:	7.5
pH:	7.4
μ:	0.052122
Lysimeter:	Overburden Upgradient of Pit 32

Input to WATEQ
(ppm)

Cations		Anions	
Ca	92.2	Cl	70
Mg	38.9	SO_4	1,350
Na	680	HCO_3	810
K	13.9	F	1.30
Sr	3.16		
		SiO_2	11.3

Mineral	Change in Free Energy of Reaction
Calcite	0.22583*
Chalcedony	0.01937
Dolomite	0.06416
Quartz	0.73256
Gypsum	-0.79059
Silica Gel	-0.64071

* Kcal Per Equiv.

TABLE D-34. GEOCHEMICAL CALCULATIONS
PIT 32
McKINLEY MINE, NEW MEXICO

Temperature, °C:	8.5
pH:	8.2
μ:	0.059944
Surface:	Highwall Pit 32

Input to WATEQ
(ppm)

Cations		Anions	
Ca	121	Cl	60
Mg	58.3	SO_4	1,740
Na	729	HCO_3	660
K	12.1	PO_4	0.36
Sr	3.82	F	2.30
Al	0.06		
		SiO_2	7.6

Mineral	Change in Free Energy of Reaction
Calcite	1.23895*
Dolomite	2.19562
Kaolinite	4.25209
Quartz	0.48756
Chalcedony	-0.22245
Gibbsite	-0.44191
Gypsum	-0.58769

* Kcal Per Equiv.

TABLE D-35. GEOCHEMICAL CALCULATIONS
HOLE 4
McKINLEY MINE, NEW MEXICO

Temperature, °C:	12.5
pH:	6.8
μ:	0.077692
Aquifer:	Coal Upgradient of Pit 5

Input to WATEQ
(ppm)

Cations		Anions	
Ca	38.2	Cl	50
Mg	12.6	SO_4	1,930
Na	1,320	HCO_3	1,380
K	6.92	F	2.30
Fe	0.4		
Sr	2.04	SiO_2	13.3
Al	0.7		
B	7.9		

Mineral	Change in Free Energy of Reaction
Chalcedony	0.03574*
$Fe(OH)_3$	3.95382
Gibbsite	1.70596
Goethite	8.69511
Kaolinite	9.10230
Quartz	0.73304
Calcite	-0.77464
Silica Gel	-0.63298

* Kcal Per Equiv.

TABLE D-36. GEOCHEMICAL CALCULATIONS
HOLE 5
McKINLEY MINE, NEW MEXICO

Temperature, °C:	13.0
pH:	7.0
μ:	0.093808
Lysimter:	Pit 5 Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	273	Cl	80
Mg	11.6	SO_4	2,800
Na	1,390	HCO_3	760
K	18.6	F	0.6
Fe	0.25		
Sr	5.14	SiO_2	22.8
Al	0.35		
B	5.9		
Mn	0.68		

Mineral	Change in Free Energy of Reaction
Calcite	0.20426*
Chalcedony	0.33650
$Fe(OH)_3$	3.77574
Gibbsite	1.73041
Goethite	8.55009
Kaolinite	9.75741
Quartz	1.03221
Birnessite	9.19850
Manganite	5.08214
Gypsum	-0.08268
Silica Gel	-0.33309
Rhodochrosite	-0.68689

* Kcal Per Equiv.

TABLE D-37. GEOCHEMICAL CALCULATIONS
LAKE (Seminoe Reservoir)
MEDICINE BOW MINE, WYOMING

Temperature, °C: 15.0
pH: 7.8
μ: 0.0052597
Surface: Outside Mine Area

Input to WATEQ
(ppm)

Cations		Anions	
Ca	31.8	Cl	22
Mg	10.2	SO_4	70.0
Na	19.9	HCO_3	113
K	2.0	PO_4	0.21
Fe	0.3	F	0.1
Al	0.08		
B	3.1	SiO_2	10.6

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	3.98266*
Goethite	8.89116
Kaolinite	5.17278
Quartz	0.53855
Calcite	-0.32397
Chalcedony	-0.15081
Gibbsite	-0.08375

* Kcal Per Equiv.

TABLE D-38. GEOCHEMICAL CALCULATIONS
P-5
MEDICINE BOW MINE, WYOMING

Temperature, °C:	9.5
pH:	5.0
μ:	0.039713
Surface:	North Ditch Creek Outside Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	215	Cl	2.7
Mg	193	SO_4	1,070
Na	95	HCO_3	189
K	8.3	PO_4	0.28
Sr	1.5	F	0.14
Al	0.5		
B	2.6	SiO_2	0.36
Mn	0.3		

Mineral	Change in Free Energy of Reaction
Birnessite	4.70035*
Manganite	0.03050
Gypsum	-0.43438

* Kcal Per Equiv.

TABLE D-39. GEOCHEMICAL CALCULATIONS
WATER TRUCK
MEDICINE BOW MINE, WYOMING

Temperature, °C:	5.0
pH:	6.5
μ:	0.043855
Check Sample:	

Input to WATEQ
(ppm)

Cations		Anions	
Ca	222	Cl	40
Mg	174	SO_4	1,560
Na	215	HCO_3	250
K	8.6	PO_4	0.25
Sr	7.0	F	0.09
B	7.7		
Mn	0.19	SiO_2	1.7

Mineral	Change in Free Energy of Reaction
Birnessite	8.64618*
Manganite	3.55806
Gypsum	-0.26507
Quartz	-0.26589

* Kcal Per Equiv.

TABLE D-40. GEOCHEMICAL CALCULATIONS
P-4
MEDICINE BOW MINE, WYOMING

Temperature, °C:	14.0
pH:	6.5
μ:	0.0542278
Surface:	Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	262	Cl	35
Mg	193	SO_4	1,760
Na	234	HCO_3	290
K	10	PO_4	0.22
Sr	8.0	F	0.09
B	3.6		
Mn	0.24	SiO_2	0.8

Mineral	Change in Free Energy of Reaction
Birnessite	7.79410*
Manganite	3.63373
Gypsum	-0.19787
Quartz	-0.91746

* Kcal Per Equiv.

TABLE D-41. GEOCHEMICAL CALCULATIONS
HOLE 33-4-1
MEDICINE BOW MINE, WYOMING

Temperature, °C:	10.0
pH:	6.5
μ:	0.0621973
Aquifer:	Coal Upgradient of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	335	Cl	37.2
Mg	252	SO_4	1,905
Na	16.5	HCO_3	589
K	7.2	PO_4	0.05
Fe	0.7	F	0.07
Sr	11.9		
Al	0.08	SiO_2	15.4
B	18.3		
Mn	0.16		

Mineral	Change in Free Energy of Reaction
Chalcedony	0.15470*
$Fe(OH)_3$	3.99596
Gibbsite	1.32274
Goethite	8.56855
Kaolinite	8.54976
Quartz	0.85995
Birnessite	7.66535
Manganite	3.18460
Calcite	-0.39993
Dolomite	-0.79934
Gypsum	-0.05864

* Kcal Per Equiv.

TABLE D-42. GEOCHEMICAL CALCULATIONS
DUPLICATE OF HOLE 33-4-1
MEDICINE BOW MINE, WYOMING

Temperature, °C:	11.0
pH:	8.2
μ:	0.07041179
Aquifer:	Coal Upgradient of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	365	Cl	52.5
Mg	257	SO_4	2,350
Na	318	HCO_3	309
K	13.8	PO_4	0.3
Sr	11.5	F	0.06
Al	0.4		
B	6.7	SiO_2	69
Mn	0.07		

Mineral	Change in Free Energy of Reaction
Calcite	1.41919*
Chalcedony	0.98065
Dolomite	2.83222
Gibbsite	0.44850
Gypsum	0.04297
Kaolinite	8.46258
Quartz	1.68272
Silica Gel	0.31452
Birnessite	11.56910
Manganite	7.15007

* Kcal Per Equiv.

TABLE D-43. GEOCHEMICAL CALCULATIONS
P-1
MEDICINE BOW MINE, WYOMING

Temperature, °C:	10.5
pH:	6.0
μ:	0.092097
Surface:	Sump Holding Pond

Input to WATEQ
(ppm)

Cations		Anions	
Ca	381	Cl	46
Mg	390	SO_4	3,190
Na	460	HCO_3	410
K	10.7	PO_4	0.5
Sr	17.2	F	0.09
Al	0.07		
B	5.7	SiO_2	5.4
Mn	0.19		

Mineral	Change in Free Energy of Reaction
Gibbsite	0.09441*
Gypsum	0.11712
Kaolinite	4.91188
Quartz	0.26524
Birnessite	6.2200
Manganite	1.84739
Chalcedony	-0.43842

* Kcal Per Equiv.

TABLE D-44. GEOCHEMICAL CALCULATIONS
P-12 (repeat of P-2)
MEDICINE BOW MINE, WYOMING

Temperature, °C:	15.0
pH:	7.9
μ:	0.1011574
Surface:	Sump Holding Pond

Input to WATEQ
(ppm)

Cations		Anions	
Ca	431	Cl	100
Mg	450	SO_4	3,516
Na	515	HCO_3	390
K	14.2	PO_4	0.18
Sr	16.3	F	0.06
Al	0.08		
B	6.20	SiO_2	2.1
Mn	0.07		

Mineral	Change in Free Energy of Reaction
Calcite	1.24618*
Dolomite	2.79861
Gypsum	0.17498
Kaolinite	2.78796
Birnessite	10.49791
Manganite	6.37141
Gibbsite	-0.36462
Quartz	-0.37315

* Kcal Per Equiv.

TABLE D-45. GEOCHEMICAL CALCULATIONS
P-2
MEDICINE BOW MINE, WYOMING

Temperature, °C:	6.5
pH:	6.0
μ:	0.1093978
Surface:	Sump Holding Pond

Input to WATEQ
(ppm)

Cations		Anions	
Ca	445	Cl	61
Mg	484	SO_4	3,950
Na	5.76	HCO_3	180
K	13.2	PO_4	0.07
Sr	17.8	F	0.07
Al	0.1		
B	5.8	SiO_2	6.1
Mn	0.15		

Mineral	Change in Free Energy of Reaction
Gibbsite	0.70796*
Gypsum	0.25491
Kaolinite	5.38493
Quartz	0.41973
Birnessite	6.96828
Manganite	2.05822
Chalcedony	-0.29664

* Kcal Per Equiv.

TABLE D-46. GEOCHEMICAL CALCULATIONS
P-3
MEDICINE BOW MINE, WYOMING

Temperature, °C:	7.0
pH:	6.0
μ:	0.11333
Surface:	Sump

Input to WATEQ
(ppm)

Cations		Anions	
Ca	515	Cl	66
Mg	495	SO_4	3,880
Na	521	HCO_3	645
K	11.2	PO_4	0.4
Sr	14.6	F	0.09
Al	0.2		
B	5.0	SiO_2	9.6
Mn	0.21		

Mineral	Change in Free Energy of Reaction
Gibbsite	0.67103*
Gypsum	0.31110
Kaolinite	0.80581
Quartz	0.66305
Birnessite	0.96088
Manganite	2.13280
Chalcedony	-0.05173

* Kcal Per Equiv.

TABLE D-47. GEOCHEMICAL CALCULATIONS
POND 4
ROSEBUD MINE, WYOMING

Temperature, °C:	14.0
pH:	7.6
μ:	0.016804
Surface:	In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	124	Cl	17
Mg	45	SO_4	472
Na	31.2	HCO_3	15
K	5.8	PO_4	0.16
Fe	0.0001	F	0.2
Sr	1.0		
		SiO_2	2.4

Mineral	Change in Free Energy of Reaction
Goethite	4.24212*
Hematite	15.76637
$Fe(OH)_3$	-0.59914
Quartz	-0.28652

* Kcal Per Equiv.

TABLE D-48. GEOCHEMICAL CALCULATIONS
POND 1
ROSEBUD MINE, WYOMING

Temperature, °C:	18.5
pH:	7.1
μ:	0.0223876
Surface:	In Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	119	Cl	23
Mg	73	SO_4	588
Na	70	HCO_3	19.4
K	9.7	PO_4	0.12
Fe	0.0001	F	0.16
Sr	2.4		
B	0.5	SiO_2	1.7

Mineral	Change in Free Energy of Reaction
Goethite	4.60974*
Hematite	16.64532
Calcite	-0.41436
Dolomite	-0.78931
$Fe(OH)_3$	-0.53438
Quartz	-0.58623

* Kcal Per Equiv.

TABLE D-49. GEOCHEMICAL CALCULATIONS
HOLE 3R4S-15-1
ROSEBUD MINE, WYOMING

Temperature, °C:	3.0
pH:	7.100
μ:	0.03692538
Aquifer:	Coal Between Rosebud and Nugget

Input to WATEQ
(ppm)

Cations		Anions	
Ca	258	Cl	9.00
Mg	126	SO_4	803
Na	90.2	HCO_3	516
K	6.42	PO_4	426
Fe	1.8	F	0.05
Sr	11.0		
Al	0.28	SiO_2	19.5
B	0.7		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	3.24194*
Gibbsite	2.12212
Goethite	7.34328
Hematite	21.61773
Kaolinite	10.55270
Quartz	1.11734
Vivianite	2.25994
Calcite	0.19423
Chalcedony	0.38985
Gypsum	-0.41009
Silica Gel	-0.26245

* Kcal Per Equiv.

TABLE D-50. GEOCHEMICAL CALCULATIONS
HOLE 3
ROSEBUD MINE, WYOMING

Temperature, °C:	9.0
pH:	6.90
μ:	0.041775
Aquifer:	Coal Between Rosebud and Nugget

Input to WATEQ
(ppm)

Cations		Anions	
Ca	208	Cl	19
Mg	113	SO_4	1,059
Na	235	HCO_3	622
K	9.3	PO_4	0.13
Sr	9.10	F	0.1
B	0.5		
Mn	0.27	SiO_2	12.6
Fe	0.2		

Mineral	Change in Free Energy of Reaction
$Fe(OH)_3$	3.40741*
Goethite	7.91256
Hematite	22.94792
Chalcedony	0.05424
Quartz	0.76267
Calcite	-0.0087
Dolomite	-0.23166
Gypsum	-0.44115
Silica Gel	-0.60843

* Kcal Per Equiv.

TABLE D-51. GEOCHEMICAL CALCULATIONS
PIT 45
ROSEBUD MINE, WYOMING

Temperature, °C:	14.00
pH:	7.9
μ:	0.0532926
Surface:	Highwall Pit

Input to WATEQ
(ppm)

Cations		Anions	
Ca	355	Cl	33
Mg	176	SO_4	1,529
Na	182	HCO_3	506
K	10	PO_4	0.05
Fe	0.0001	F	0.09
Sr	10.7		
B	2.4	SiO_2	8.1
Mn	0.14		

Mineral	Change in Free Energy of Reaction
Calcite	1.48458*
Dolomite	2.81624
Goethite	4.15108
Hematite	15.58462
Quartz	0.41213
Rhodochrosite	-0.45198
Chalcedony	-0.28040
$Fe(OH)_3$	-0.69051
Gypsum	-0.09759

* Kcal Per Equiv.

TABLE D-52. GEOCHEMICAL CALCULATIONS
HOLE 2
ROSEBUD MINE, WYOMING

Temperature° C:	10
pH:	6.9
μ:	0.0545726
Aquifer:	Undesignated Overburden Above Coal Between Rosebud and Nugget

Input to WATEQ
(ppm)

Cations		Anions	
Ca	345	Cl	29
Mg	231	SO_4	1,546
Na	89	HCO_3	549
K	8.0	PO_4	0.1
Fe	0.0001	F	0.15
Sr	7.6		
B	1.1	SiO_2	16.3
Mn	0.22		

Mineral	Change in Free Energy of Reaction
Goethite	3.73813*
Hematite	14.63101
Quartz	0.89019
Calcite	0.14542
Chalcedony	0.18495
Dolomite	0.22274
Gypsum	-0.10417
Silica Gel	-0.47945

* Kcal Per Equiv.

TABLE D-53. GEOCHEMICAL CALCULATIONS
HOLE 1
ROSEBUD MINE, WYOMING

Temperature, °C:	11.8
pH:	7.00
μ:	0.1042478
Aquifer:	Above Coal Between Rosebud and Nugget

Input to WATEQ
(ppm)

Ca	609	Cl	65
Mg	550	SO_4	3,465
Na	163	HCO_3	805
K	9.0	PO_4	0.19
Fe	0.10	F	0.14
Sr	11.2		
Al	0.3	SiO_2	21.4
B	1.9		
Mn	2.39		

Mineral	Change in Free Energy of Reaction
Dolomite	1.41786*
$Fe(OH)_3$	3.18665
Gibbsite	1.71936
Goethite	7.88061
Gypsum	0.34318
Hematite	22.97383
Kaolin	9.69009
Quartz	1.01918
Calcite	0.63363
Chalcedony	0.31965
Rhodochrosite	-0.02485

* Kcal Per Equiv.

TABLE D-54. GEOCHEMICAL CALCULATIONS
POND N-1
ROSEBUD MINE, WYOMING

Temperature, °C:	15.0
pH:	3.5
μ:	0.1131910
Surface:	At Nugget Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	463	Cl	38
Mg	747	SO_4	4,495
Na	73	PO_4	0.13
K	19.1	F	0.59
Fe	9.3		
Sr	4.2	SiO_2	24.4
Al	15.2		
Mn	9.42		

Mineral	Change in Free Energy of Reaction
Goethite	2.72662*
Hematite	12.76795
Quartz	1.03754
Chalcedony	0.34818
Gypsum	0.25412
Silica Gel	-0.32486

* Kcal Per Equiv.

TABLE D-55. GEOCHEMICAL CALCULATIONS
POND N-2
ROSEBUD MINE, WYOMING

Temperature, °C:	11.5
pH:	7.7
μ:	0.1327267
Surface:	At Nugget Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	522	Cl	73
Mg	970	SO_4	4,885
Na	128	HCO_3	351
K	38.2	PO_4	0.97
Fe	0.001	F	0.44
Sr	6.0		
		SiO_2	4.0

Mineral	Change in Free Energy of Reaction
Dolomite	2.32162*
Goethite	5.24579
Hematite	17.69472
$Fe(OH)_3$	0.57190
Gypsum	0.31628
Quartz	0.07867
Calcite	-2.3764
Chalcedony	-0.62182

* Kcal Per Equiv.

TABLE D-56. GEOCHEMICAL CALCULATIONS
POND N-3
ROSEBUD MINE, WYOMING

Temperature, °C:	15.0
pH:	7.9
μ:	0.15184
Surface:	At Nugget Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	481	Cl	95
Mg	1,170	SO_4	5,844
Na	202	HCO_3	339
K	34.5	PO_4	0.19
Fe	0.0001	F	0.33
Sr	6.2		
B	0.85	SiO_2	1.0
Mn	0.37		

Mineral	Change in Free Energy of Reaction
Calcite	1.07943*
Dolomite	2.95648
Goethite	4.22205
Gypsum	0.28874
$Fe(OH)_3$	-0.68751
Quartz	-0.78964

* Kcal Per Equiv.

TABLE D-57. GEOCHEMICAL CALCULATIONS
POND N-4
ROSEBUD MINE, WYOMING

Temperature, °C:	13.0
pH:	8.3
μ:	0.4596135
Surface:	At Nugget Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	411	Cl	560
Mg	4,870	SO_4	18,854
Na	1,100	HCO_3	623
K	60	PO_4	0.7
Fe	0.2	F	0.66
Sr	5.4		
Al	0.6	SiO_2	0.4
B	0.7		
Mn	0.44		

Mineral	Change in Free Energy of Reaction
Calcite	1.39633*
Dolomite	4.46643
$Fe(OH)_3$	3.38892
Goethite	8.16354
Gypsum	0.32146
Hematite	23.58091
Kaolinite	2.56887
Gibbsite	0.38030
Gypsum	0.32146
Manganite	0.35976
Rhodochrosite	0.23932

* Kcal Per Equiv.

TABLE D-58. GEOCHEMICAL CALCULATIONS
PIT 1G
KEMMERER MINE, WYOMING

Temperature, °C:	19
pH:	8.0
μ:	0.06184324
Surface:	Highwall Pit 1G

Input to WATEQ
(ppm)

Cations		Anions	
Ca	382	Cl	19.0
Mg	344	SO_4	2,025
Na	44.8	HCO_3	146.7
K	20.1	PO_4	0.98
Fe	0.77	F	0.2
Sr	5.55		
Al	0.28	SiO_2	0.70
B	0.4		
Mn	0.39		

Mineral	Change in Free Energy of Reaction
Calcite	0.98681*
Dolomite	2.25988
$Fe(OH)_3$	4.61458
Gibbsite	0.00891
Goethite	9.79258
Kaolinite	2.11976
Birnessite	11.44777
Manganite	7.74572
Gypsum	-0.01959

* Kcal Per Equiv.

TABLE D-59. GEOCHEMICAL CALCULATIONS
POND 1
WYODAK MINE, WYOMING

Temperature, °C:	26
pH:	7.4
μ:	0.05071813
Surface:	Holding Pond, North Pit

Input to WATEQ
(ppm)

Cations		Anions	
Ca	295	Cl	19
Mg	164	SO_4	1,390
Na	276	HCO_3	545.1
K	25	PO_4	0.43
Sr	4.51	F	0.5
Al	0.15		
Mn	0.07	SiO_2	11.3

Mineral	Change in Free Energy of Reaction
Calcite	1.04583*
Dolomite	2.18231
Gibbsite	0.02835
Kaolinite	5.23041
Quartz	0.36859
Birnessite	7.93005
Manganite	5.01075
Gypsum	-0.28498

* Kcal Per Equiv.

TABLE D-60. GEOCHEMICAL CALCULATIONS
HIGHWALL
WYODAK MINE, WYOMING

Temperature, °C:	21
pH:	7.4
μ:	0.06845261
Surface:	Highwall Pit Fed by Donkey Creek

Input to WATEQ
(ppm)

Cations		Anions	
Ca	425	Cl	263
Mg	249	SO_4	1,701
Na	338	HCO_3	563.7
K	17.9	PO_4	3.37
Fe	0.42	F	0.76
Sr	5.21		
Al	0.06	SiO_2	14.5
Mn	1.0		

Mineral	Change in Free Energy of Reaction
Calcite	1.10904*
Dolomite	2.27844
$Fe(OH)_3$	4.50618
Goethite	4.81897
Hematite	27.14406
Kaolinite	5.14682
Quartz	0.61584
Birnessite	9.83249
Manganite	6.47736
Rhodochrosite	0.14216
Hydroxyapatite	5.48098
Chalcedony	-0.05445
Gibbsite	-0.22137
Gypsum	-0.005910

* Kcal Per Equiv.

TABLE D-61. GEOCHEMICAL CALCULATIONS
DONKEY CREEK
WYODAK MINE, WYOMING

Temperature, °C:	29.0
pH:	8.2
μ:	0.06386426
Surface:	Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	250	Cl	203
Mg	294	SO_4	1,714
Na	366	HCO_3	492.9
K	20.1	PO_4	12.0
Sr	4.02	F	1.63
Al	0.13		
B	0.20	SiO_2	18.0
Mn	0.35		

Mineral	Change in Free Energy of Reaction
Calcite	1.92933*
Dolomite	4.43266
Hydroxyapatite	11.34570
Kaolinite	2.90549
Quartz	0.57623
Sepiolite	2.38001
Birnessite	10.70934
Manganite	8.04570
Rhodochrosite	0.53323
Chalcedony	-0.06865
Gypsum	-0.38653

* Kcal Per Equiv.

TABLE D-62. GEOCHEMICAL CALCULATIONS
SPRING
COLSTRIP MINE, MONTANA

Temperature, °C:	21
pH:	7.8
μ:	0.02111439
Surface:	Upstream of Mine

Input to WATEQ
(ppm)

Cations		Anions	
Ca	119	Cl	5.0
Mg	92.5	SO_4	397
Na	21.1	HCO_3	401
K	8.12	PO_4	0.37
Sr	2.01	F	0.76
Al	0.08		
		SiO_2	24.5

Mineral	Change in Free Energy of Reaction
Calcite	1.02326*
Chalcedony	0.23113
Dolomite	2.25521
Kaolinite	5.14633
Quartz	0.91143
Gibbsite	-0.51696
Silica Gel	-0.44228

* Kcal Per Equiv.

TABLE D-63. GEOCHEMICAL CALCULATIONS
SWIMMING HOLE
COLSTRIP MINE, MONTANA

Temperature, °C:	25
pH:	7.6
μ:	0.9860988
Surface:	In Area E Spoils

Input to WATEQ
(ppm)

Cations		Anions	
Ca	319	Cl	18.0
Mg	696	SO_4	3,769
Na	151	HCO_3	175.1
K	18.2	PO_4	0.37
Sr	5.25		
Al	0.11	SiO_2	0.8
B	0.40		
Mn	0.05		

Mineral	Change in Free Energy of Reaction
Calcite	0.40595*
Dolomite	1.71858
Kaolinite	1.22978
Gibbsite	-0.42171
Gypsum	-0.02737

* Kcal Per Equiv.

TABLE D-64. GEOCHEMICAL CALCULATIONS
D-1
COLSTRIP MINE, MONTANA

Temperature, °C:	22
pH:	7.6
μ:	0.0813269
Surface:	Area D Pit

Input to WATEQ
(ppm)

Cations		Anions	
Ca	283	Cl	9.0
Mg	578	SO_4	3,015
Na	11.4	HCO_3	250.1
K	18.4	PO_4	7.76
Sr	6.5		
Al	0.04	SiO_2	1.0
B	0.6		

Mineral	Change in Free Energy of Reaction
Calcite	0.055121*
Dolomite	1.92089
Kaolinite	0.81895
Gypsum	-0.11955

* Kcal Per Equiv.

TABLE D-65. GEOCHEMICAL CALCULATIONS
D-2
COLSTRIP MINE, MONTANA

Temperature, °C:	24
pH:	8.7
μ:	0.1242215
Surface:	Area D Pit

Input to WATEQ
(ppm)

Cations		Anions	
Ca	265	Cl	22
Mg	864	SO_4	5,043
Na	219	HCO_3	549.1
K	45.9	PO_4	0.35
Sr	5.51	F	0.05
Al	0.1		
B	1.6	SiO_2	5.0

Mineral	Change in Free Energy of Reaction
Calcite	2.16425*
Dolomite	5.46618
Kaolinite	0.32601
Chalcedony	-0.76717
Gypsum	-0.08842
Quartz	-0.10641

* Kcal Per Equiv.